Journal and Proceedings of the Royal Society of New South Wales

VOLUME 116 1983 PARTS 3 and 4
Nos. 329 and 330)

Published by the Society
P.O. Box N112, Grosvenor Street, N.S.W. 2000
Issued December, 1983
ISSN 0035 - 9173

THE ROYAL SOCIETY OF NEW SOUTH WALES

Address:— Royal Society of New South Wales,
PO Box N112 Grosvenor Street,
NSW 2000,
Australia.

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ISSN 0035-9173

JOURNAL AND PROCEEDINGS

OF THE

ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 116

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(Nos. 329 and 330)

1983

ISSN 0035-9173

PUBLISHED BY THE SOCIETY
PO BOX N112, GROSVENOR STREET, NSW 2000

Journal and Proceedings, Royal Society of New South Wales, Vol. 116, pp. 53-70, 1983
ISSN 0035-9173/83/020053 — 18 $4.00/1

Sydney Southern Star Catalogue

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ABSTRACT. A catalogue of 26926 star positions to be known as the Sydney Southern Star Catalogue (SSSC) has been produced at Sydney Observatory, principally covering the declination range between -51° 00' and -63° 30'. Some 3244 faint Astrographic Catalogue stars were included to supplement the stars at fainter magnitudes. The standard error of a catalogue position based on four images is 0".10 in either coordinate. The reference catalogue used was the WL50.

INTRODUCTION

Due to the recent decision by the New South Wales Government to cease astronomical research at Sydney Observatory, it became urgent to publish the results of our astrometric programme over the last few years. Although some 1452 plates have been taken since 1964 covering from declination -36 degrees to the south celestial pole, only 501 were able to be measured. Measuring commenced when the Grubb-Parsons photoelectric measuring machine became operational in 1975.

The results of the measurement of the declination zones centred on -53° 30', -56° 00', -58° 30', -61° 00' and -63° 30' are presented here and are available on microfiche and computer tape. A catalogue covering the zone -48° to -54° based on plates taken at Sydney Observatory has recently been published by Eichhorn (SPC).

THE PLATES

The plates were each exposed for six minutes with the 23cm Taylor, Taylor and Hobson camera with manual guiding in right ascension only. The lens has a focal length of 1776.6mm. The plates are 20cm square Ilford Rapid Process Experimental Emulsion, allowing a possible sky coverage of six degrees square with a scale of 116".1 per millimetre. A 2.3 magnitude diffraction grating was used to produce side images shifted from the central image in declination. A central spot is placed on each plate before removal from the plate holder.

The plates have full overlap in both right ascension and declination. Table 1 gives the plate information for each zone. Detailed information for each plate is available on the computer tape containing measured positions.

TABLE 1

ZONE	FIRST R.A. OF CENTRE	PLATE SEPARATION	NUMBER OF PLATES	EPOCH RANGE
$-53^\circ30'$	0^h00^m	16^m	90	1966.803 - 1967.836
$-56^\circ00'$	0^h08^m	16^m	90	1968.730 - 1969.668
$-58^\circ30'$	0^h00^m	18^m	80	1969.515 - 1981.093
$-61^\circ00'$	0^h09^m	18^m	80	1970.501 - 1982.573
$-63^\circ30'$	0^h00^m	20^m	71*	1971.630 - 1972.546

* The plate 20^h40^m, $-63^\circ30'$ has not been taken.

MEASUREMENT

The stars selected for measurement were compiled from the Cape Photographic Catalogue for 1950 (CPC), International Reference Stars (IRS), Cape Zone Catalogue for 1900 (ZC), Albany General Catalogue (GC) and the Sydney Astrographic Catalogue (AC). The AC was used to obtain supplementary faint stars so that about one star per square degree is in the photographic magnitude range 11.0 to 11.5. All these stars were given a magnitude of 12.0 to distinguish them as AC stars. In the area south of $-63^\circ30'$, only the IRS stars were selected for measurement. This was to give complete plate coverage for the determination of plate constants for plates centred at $-63^\circ30'$. CPC stars and AC stars were selected for measurement between declinations -52° and $-63^\circ30'$. Between -51° and -52°, the measuring list was prepared by supplementing the few CPC stars in this area with ZC stars, GC stars and IRS stars. In general, stars brighter than photographic magnitude 6.0 were excluded and stars brighter than photographic magnitude 8.1 had their first order side images measured as well as the central image, giving three measurements.

All the catalogue coordinates were converted to standard coordinates which represent the first order

predicted position of the stars on each plate. The plates were then measured in a Grubb-Parsons photoelectric measuring machine. The plate centre spot is given the x-y coordinates (100000, 100000), the units being in microns. On this plate scale, one micron represents 0.12 seconds of arc. The x and y axes are approximately parallel to right ascension and declination respectively. Stars are only measured if both the x and y coordinates are between 15000 and 185000.

The first 20 stars measured on the plate were selected so as to cover a large area of the plate and a magnitude range from 8.1 to 10.5. When these stars were measured, their standard and measured coordinates were compared with an eight plate constant solution of the form:-

$$\Delta x = \xi - x = Ax + By + C + M(m-10)$$
$$\Delta y = \eta - y = Dx + Ey + F + N(m-10)$$

where ξ, η are the standard coordinates and m is the photographic magnitude. This plate constant solution was then used to convert the stars' standard coordinates into a second order predicted position. These computations were all carried out on a Diehl Alphatronic programmable calculator which was connected through an interface to the x-y coordinates of the measuring machine.

For each subsequent image, after the first 20, the measured and predicted position were compared to assure the correct image was measured. Any difference greater than 60 microns produced a warning tone so that the result could be checked and if necessary, corrected. After each 100 images were measured, a check star was remeasured to check for measuring machine drift. If the difference exceeded three microns, then the plate was remeasured. After successful completion, the plate was rotated 180 degrees, still with the emulsion downwards. The same measuring procedure was again followed with the first measurement positions known as direct coordinates, replacing the original standard coordinates. The second set of measured positions are known as reverse coordinates.

The reverse coordinates were then converted into the same coordinate system as the direct by using six reverse to direct plate constants applied to the first 20 stars. That is:-

$$\Delta x = x_d - x_r = ax_r + by_r + c$$

$$\Delta y = y_d - y_r = dx_r + ey_r + f$$

The average of the direct and reverse positions is given by:-

$$x_a = (2x_d - ax_r - by_r - c)/2$$

$$y_a = (2y_d - dx_r - ey_r - f)/2$$

and these values were then stored on magnetic tape. The purpose of averaging the direct and reverse measures in this manner is to avoid the introduction of magnitude terms produced by the measuring machine.

REDUCTION

The plates centred on declination $-53^{\circ}30'$ were the first to be measured. At that time the measured positions of each star were not interfaced immediately into the microprocessor. As a result, about 30% of the stars were either incorrectly measured at the time or incorrectly typed into the microprocessor later. This meant that almost every plate in this zone had to be remeasured. The remeasured stars were compiled from the reference stars on the plate and the previously incorrectly measured stars. It then became necessary to convert at least two sets of measurements into the one coordinate system. This was done by excluding the incorrectly measured stars from the first set of measurements and then applying a ten plate constant solution of the form:-

$$\xi - x = ax + by + c + px^2 + qxy$$

$$\eta - y = a'x + b'y + c' + p'xy + q'y^2$$

to the Perth 70 reference stars. Subsequently all the measured positions were converted into right ascension and declination coordinates. The same procedure was followed for the second set of measurements. Then, using the second set of plate constants, the first set of right ascensions and declinations were converted back into their predicted x-y positions on the second measurement run. Thus, when the second set of plate constants is used on all the x-y coordinates, the previously calculated right ascensions and declinations are produced. For the plates in the $-53^{\circ}30'$ zone centred at right ascensions 5^h04^m and 7^h12^m to 16^h48^m no plate constants were kept, only the final spherical coordinates, even though there was at least one remeasurement of each plate. In these cases the right ascensions and declinations were converted to x-y positions assuming that each of the ten plate constants was zero.

Plate constant solutions were derived for all plates using Perth 70 reference stars and the above ten plate constant solution. The plate constants, average positions and the magnitudes were all transferred

via a telephone modem onto hard disk on the New South Wales Public Service Burroughs 7700 computer. The remainder of the reduction was carried out on this computer. Machine readable tape versions of the CPC, Perth 70 and Washington El Leoncito (WL50) catalogues were also placed on computer. The ZC, GC and IRS stars that were measured north of declination -52 degrees had their catalogue identification numbers, right ascensions, declinations and magnitudes all punched onto the computer by hand.

Once on computer, all the side image pairs were then averaged to give a single position which corresponds approximately with the central image position. This side image average position was, for the time being, considered as a separate image to the central image. A star type register (IBS) is used to record whether the image stands alone (0), is a central image (1) or is the average of the two side images (2).

Using the existing plate constants derived using the Perth 70 reference stars, the right ascensions and declinations of each image was then computed. These computed right ascensions and declinations were then used to search for their corresponding identification numbers in the existing catalogues. If the closest catalogue star was within a preset radius, then the image was given the catalogue star's identification number and photographic magnitude. If there was no photographic magnitude present on the CPC catalogue, then the visual magnitude was converted to a photographic magnitude using the following formulas:-

If SPEC < 30 $\quad M_{pg} = M_v - 0.35$

If 30 ≤ SPEC < 65 $\quad M_{pg} = M_v - 1.194 + 0.02914 \times SPEC$

If 65 ≤ SPEC $\quad M_{pg} = M_v - 2.355 + 0.04700 \times SPEC$

SPEC is the two digit spectral number code present on the CPC tape. These formulas were derived by fitting three lines to a graph compiled by averaging 36 randomly selected colour indices for each of the spectral types B0, B5, A0, A5, F0, F5, G0, G5, K0, K5 and M0 from the CPC.

Due to the likelihood that the Perth 70 IRS stars have a systematic difference from the fundamental reference frame defined by FK4, it was decided to use the WL50 catalogue instead. The plate constants were subsequently recomputed using only seven distinct constants. The plate constant solution is discussed in the next section. Right ascensions and declinations were then all recomputed using the new plate constants. This completed the machine readable version of a computer tape which shall be known as Sydney Measured Positions.

For each of the eight magnitude ranges of 5.00-5.99, 6.00-6.99, 7.00-7.99, 8.00-8.99, 9.00-9.99, 10.00-10.99, 11.00-11.99 and 12.00 all the relevant image results were extracted from the Sydney Measured Positions tape. All the AC stars being designated as magnitude 12.00 to separate them from the rest. The side image and central image positions on the same plate are averaged giving twice the weight to the side image position than the central image position. At this stage a comparison between central and side image positions was made. The difference between central and side image positions in the sense central minus side, for 9173 stars averaged out as $-0\overset{''}{.}0203 \pm 0\overset{''}{.}0027$ in right ascension and $+0\overset{''}{.}0379 \pm 0\overset{''}{.}0026$ in declination. If the difference between central and side image positions was greater than 2 seconds of arc, the central image was rejected.

If results existed for the same identification number on two or more plates, then the right ascensions, declinations and epochs were averaged and the standard deviations calculated. If any standard deviation exceeded 0.6 seconds of arc in either right ascension or declination then the plate which resulted in the largest deviation from the average was rejected from the average calculation. This was continued if necessary until both right ascension and declination standard deviations were less than 0.6 seconds of arc. If only two plates remained and either of the standard deviations still exceeded 0.6 seconds of arc then that star was totally rejected. The following table shows both the number of images and the number of stars rejected as a result of this procedure for each magnitude range.

TABLE 2

Magnitude Range	Final Number of images used	Number of images rejected	Percentage	Number of stars rejected
5.00- 5.99	67	5	7.46	3
6.00- 6.99	1770	8	0.45	8
7.00- 7.99	6461	31	0.48	16
8.00- 8.99	19106	62	0.32	51
9.00- 9.99	34237	72	0.21	68
10.00-10.99	28113	63	0.22	32
11.00-11.99	3648	26	0.71	4
12.00	11157	150	1.34	119
ALL	104559	417	0.40	301

All the faint AC stars and stars south of declination -63° 30' were then separated from the remainder of the star positions. This was because neither have proper motions calculated and the stars south of

$-63^\circ 30'$ are incomplete since they are primarily reference stars. Thus, the Sydney Southern Star Catalogue is comprised of three sections. First, 23287 stars between $-51^\circ 00'$ and $-63^\circ 30'$, secondly 3244 faint AC stars and lastly 395 stars south of $-63^\circ 30'$. The method of determining the proper motions of the first section is described later.

THE PLATE CONSTANTS

The relationship between the standard coordinates (ξ,η) and the measured coordinates (x,y) of the stars' images on a photographic plate is given by a model of form

$$\xi = \xi(x,y,m,c)$$
$$\eta = \eta(x,y,m,c)$$

where m is magnitude and c is colour index. In the initial reduction of the measurements using the Perth 70 catalogue the following model was used:-

$$\xi - x = ax + by + c + px^2 + qxy$$
$$\eta - y = a'x + b'y + c' + p'xy + q'y^2$$

Before the final reductions were made using the Washington El Leoncito (WL50) catalogue the opportunity was taken to re-examine the question of the most appropriate model.

Magnitude dependent terms are best found using the objective grating technique (Eichhorn, 1974). A coarse grating with a grating constant of 2.3 magnitudes had been used for all plates. The difference between the mean of the side images and the central image was found for all stars on 12 plates in the $-58^\circ 30'$ zone with centres from $15^h 00^m$ to $18^h 18^m$. Denoting the differences in x as Δx and y as Δy, the model

$$\Delta x = k_1 + k_2 x$$
$$\Delta y = k_1' + k_2' y$$

was fitted to the data by least squares. Here k_1, k_1' are equivalent to magnitude terms and k_2, k_2' to coma terms. The k_1 and k_2' terms were not significant at the 2σ level on any of the plates. The k_1' and the k_2 terms were each significant on 3 of the plates. In order to get an average value for these terms the data from the 12 plates were combined and the above model fitted to this combined data. After rejecting one star with a high residual, k_1 and k_2' were found to be not significant while k_1' and k_2 were. The values of both k_1' and k_2 were small, equivalent to 0.14 microns/magnitude and 0.25 microns/magnitude (at the edge of the plate), respectively. Thus magnitude and coma terms were disregarded in the plate constant solution.

Terms involving x and y were examined using 17 plates in the $-58^\circ 30'$ zone from $0^h 00^m$ to $4^h 48^m$. Eleven different models were calculated using reference stars taken from both the Perth 70 and the WL50 catalogues. The models are given in Table 3, which also show the rms residual for both ξ and η meaned over the 17 plates for each model. The rms's were calculated taking into account the number of degrees of freedom used up by each model. The terms with coefficients P, Q and R (and P',Q'and R') allow for various distortions in the lens, such as radial and decentering distortions. For these terms to have physical reality they should have the same values on all plates and the same value for ξ and η. In fact, these terms were rarely significant at the 2σ level and did not seem to be correlated from plate to plate. As can be seen from Table 3 their contribution to the reduction in the rms is small. The p and q terms in model 1 are significant on most plates, although still very small. They result in a somewhat greater reduction in the rms than the P, Q and R terms. Thus it was clear that model 1 is basically the best model.

It is important to try to reduce the number of parameters of the fit to a minimum, especially as the WL50 catalogue contains slightly smaller number of stars than Perth 70. Within the errors the b coefficient and the negative of the a' coefficient were generally equal. Model 10 was then calculated in which they were forced to be equal. The fit of this model was only slightly worse than that of model 1. The p and q terms of models 1 and 10 are only physically meaningful if they are equal for ξ and η, in which case they can be regarded as due to tilt. In model 11 they were forced to be equal. The fit of this model with only seven parameters was worse than the fit of models 1 or 10, but still better than most of the other models. Thus it was adopted as the final model.

The smallness of all terms other than the basic a, b and c terms for the Taylor, Taylor and Hobson lens was not surprising. Fifteen plates taken by the TTH lens were utilised in the Yale catalogue for declinations -40° to -50° (Hoffleit, 1970). The least squares plate solutions, which include full second order terms as well as magnitude and coma terms, were published. In these solutions, apart from the basic a,b,c coefficients, the rest of the coefficients were significant on few, if any, of the plates.

TABLE 3

No.	MODEL	rms,WL50 (microns)	rms,Perth (microns)
1	$\xi - x = ax + by + c + px^2 + qxy$	1.701	1.382
	$\eta - y = a'x + b'y + c' + p'xy + q'y^2$	1.909	1.951
2	$\xi - x = ax + by + c + px^2 + qxy + ry^2$	1.681	1.377
	$\eta - y = a'x + b'y + c' + p'x^2 + q'xy + r'y^2$	1.928	1.936
3	$\xi - x = ax + by + c + px^2 + qxy + ry^2 + Rx(x^2 + y^2)$	1.681	1.358
	$\eta - y = a'x + b'y + c' + p'x^2 + q'xy + r'y^2 + R'y(x^2 + y^2)$	1.929	1.930
4	$\xi - x = ax + by + c + qxy + ry^2 + Rx(x^2 + y^2)$	1.778	1.449
	$\eta - y = a'x + b'y + c' + p'x^2 + q'xy + R'y(x^2 + y^2)$	1.971	2.026
5	$\xi - x = ax + by + c + P(x^2 + y^2) + Rx(x^2 + y^2)$	1.948	1.595
	$\eta - y = a'x + b'y + c' + P'(x^2 + y^2) + R'y(x^2 + y^2)$	1.991	2.053
6	$\xi - x = ax + by + c$	1.972	1.670
	$\eta - y = a'x + b'y + c'$	1.989	2.100
7	$\xi - x = ax + by + c + Q(x^2 + y^2)^{1.5}$	1.942	1.609
	$\eta - y = a'x + b'y + c' + Q'(x^2 + y^2)^{1.5}$	1.990	2.059
8	$\xi - x = ax + by + c + qxy$	1.791	1.468
	$\eta - y = a'x + b'y + c' + q'xy$	1.955	2.051
9	$\xi - x = ax + by + c + qxy + Q(x^2 + y^2)^{1.5}$	1.776	1.432
	$\eta - y = a'x + b'y + c' + q'xy + Q'(x^2 + y^2)^{1.5}$	1.963	2.014
10	$\xi - x = ax + by + c + px^2 + qxy$	1.702	1.377
	$\eta - y = -bx + dy + e + p'xy + q'y^2$	1.914	1.968
11	$\xi - x = ax + by + c + px^2 + qxy$	1.739	1.393
	$\eta - y = -bx + dy + e + pxy + qy^2$	1.946	2.021

The procedure adopted for calculating the final plate constants on each plate was as follows:-

(a) the model
$$\xi - x = ax + by + c + px^2 + qxy$$
$$\eta - y = a'x + b'y + c' + p'xy + q'y^2$$
was fitted to the reference stars. If any star had a residual in ξ and η greater than 4 microns the star was rejected and the model recalculated. This was continued until there were no stars with residuals greater than 4 microns.

(b) the model
$$\xi - x = ax + by + c + px^2 + qxy$$
$$\eta - y = -bx + dy + e + pxy + qy^2$$
was fitted to the remaining reference stars. In calculating the model the weights used for $\xi - x$ and $\eta - y$ were the inverses of the variances calculated for each equation in step (a).

ERRORS

When the observations of each star on different plates were combined, the standard deviation from the mean was calculated for each star in right ascension and declination. These results are plotted as histograms in figures 1 to 14. For each magnitude from 6 to 12 the figures show separately for right ascension and declination the standard deviation for stars with 2, 3, 4 and 5 observations and for all stars.

In order to look for systematic variations the standard deviations were averaged (by summing the variances) in terms of magnitude and number of observations. These are shown in Table 4. No clear trend with number of observations can be discerned. The standard deviations of stars with 2 observations seem slightly lower than the rest, but this is probably artificial. There is, however, some variation as a function of magnitude. The standard deviation of bright star, magnitude ≤ 6 and faint star, magnitude ≥ 11, observations are somewhat higher than for the rest of the stars.

TABLE 4

STANDARD DEVIATIONS OF INDIVIDUAL OBSERVATIONS*

NUMBER OF OBSERVATIONS		MAGNITUDE RANGE <6	6	7	8	9	10	11	12	ALL
2	n	11	80	347	1355	1731	1134	122	847	5627
	σ_α	30	21	18	18	17	17	20	22	18
	σ_δ	21	20	17	15	14	14	20	21	16
3	n	4	21	58	227	369	281	47	260	1267
	σ_α	20	22	21	21	19	21	27	29	22
	σ_δ	21	17	19	17	16	18	25	28	20
4	n	2	189	666	1860	3410	2849	380	2002	11358
	σ_α	27	23	19	21	20	21	24	26	21
	σ_δ	21	23	16	16	15	17	24	26	19
5	n	5	134	536	1513	2894	2484	309	135	8010
	σ_α	28	25	20	21	20	22	26	27	21
	σ_δ	22	22	18	17	17	18	25	26	18
6	n	-	19	38	112	246	187	33	-	635
	σ_α	-	24	22	22	22	22	26	-	22
	σ_δ	-	25	19	19	18	19	25	-	19
7	n	-	1	3	4	6	8	-	-	22
	σ_α	-	12	31	25	18	17	-	-	21
	σ_δ	-	6	30	18	17	18	-	-	20
8	n	-	-	-	1	5	1	-	-	7
	σ_α	-	-	-	22	26	9	-	-	24
	σ_δ	-	-	-	18	19	16	-	-	18
ALL	n	22	444	1648	5072	8661	6944	891	3244	26926
	σ_α	28	23	19	20	19	21	24	25	21
	σ_δ	21	22	17	16	16	17	24	25	18

*(units of standard deviation $0''.01$)

The data were combined on the basis of the above results into a table, Table 5, giving the standard error of any catalogue position. It was assumed that the standard deviation of a single observation is not dependent on the number of observations, but only dependent on which of three magnitude ranges the star falls in. The standard error of a mean position was calculated by dividing the appropriate standard deviation of a single observation by the square root of the number of observations.

TABLE 5

POSITION STANDARD ERRORS*

NUMBER OF OBSERVATIONS	MAGNITUDE RANGE ≤ 6 σ_α	≤ 6 σ_δ	7 - 10 σ_α	7 - 10 σ_δ	≥ 11 σ_α	≥ 11 σ_δ
2	16	16	14	11	18	18
3	13	13	12	9	14	14
4	12	11	10	8	13	13
5	10	10	9	7	11	11
6	9	9	8	7	10	10
7	9	8	8	6	-	-
8	-	-	7	6	-	-

*(units of standard error $0''.01$)

Figures 1 - 14. Histograms of standard deviation (in 0".01 units) from the mean for stars with

2 observations - - -
3 observations — —
4 observations —— ——
5 observations —— -
all stars ————

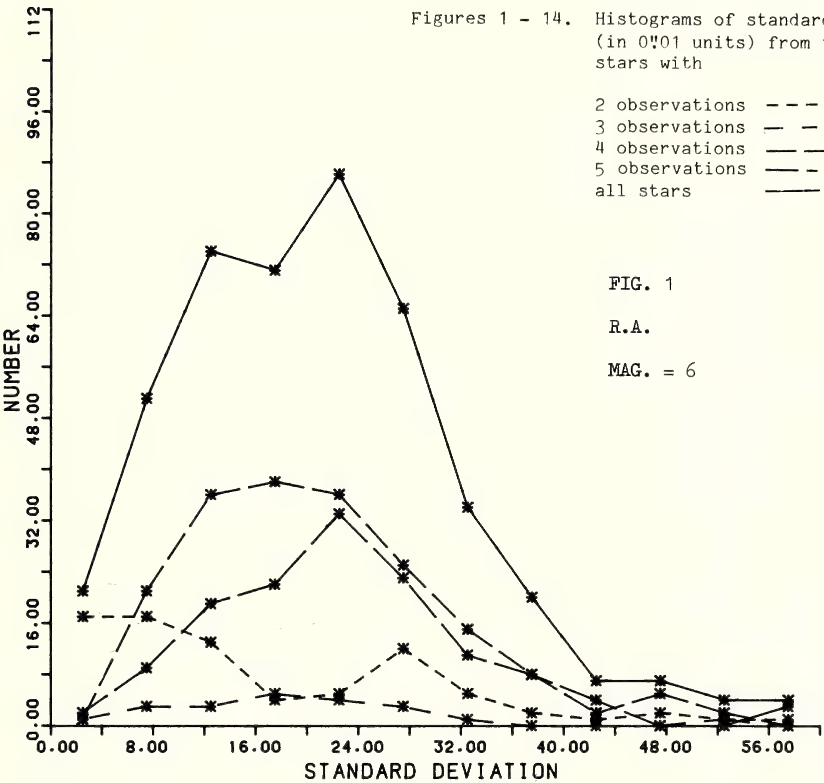

FIG. 1

R.A.

MAG. = 6

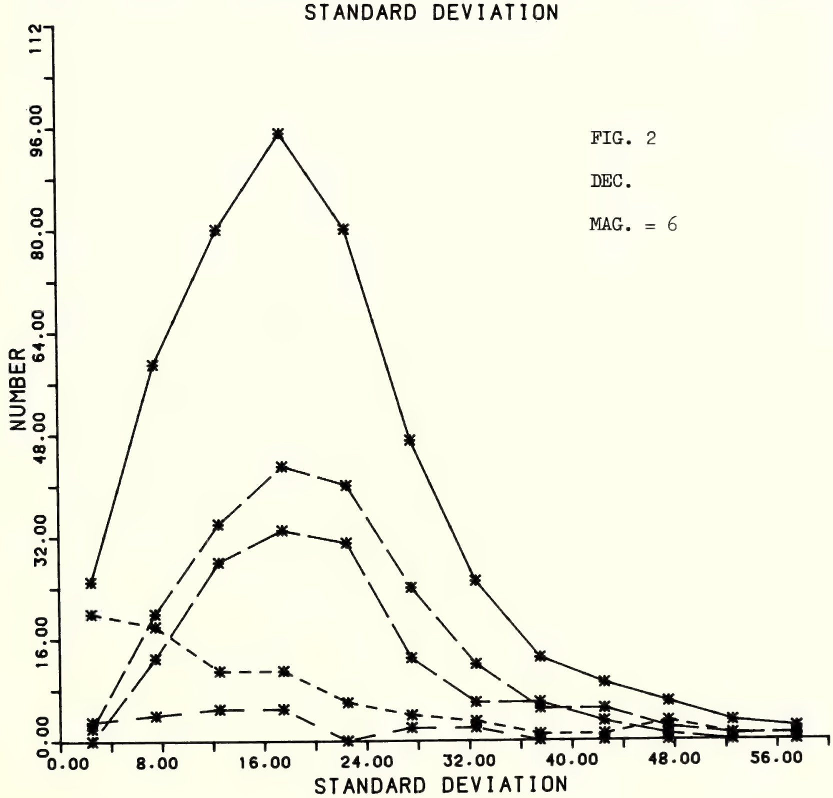

FIG. 2

DEC.

MAG. = 6

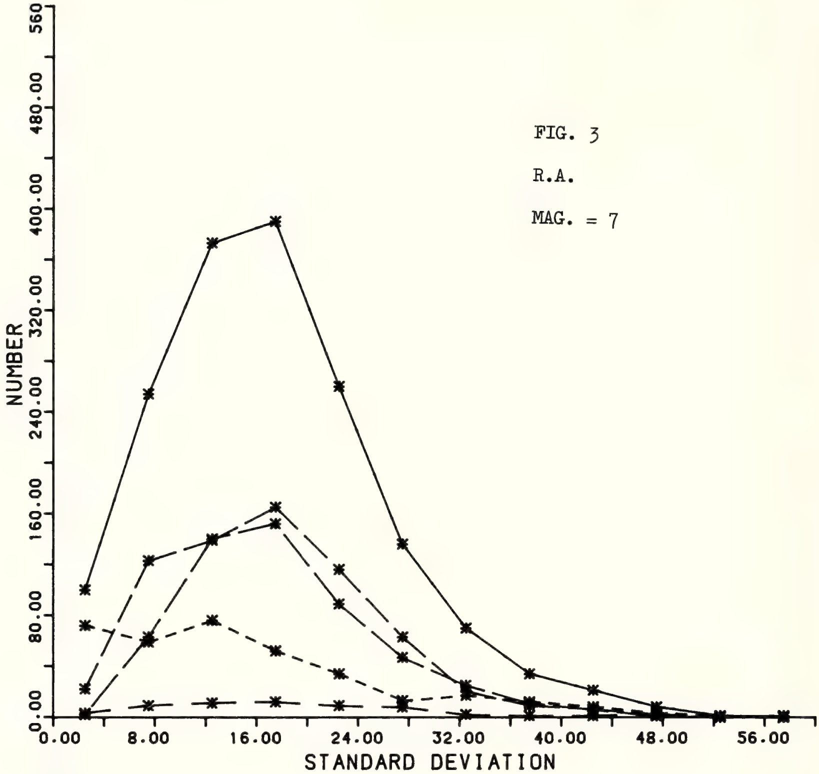
FIG. 3
R.A.
MAG. = 7
NUMBER
STANDARD DEVIATION

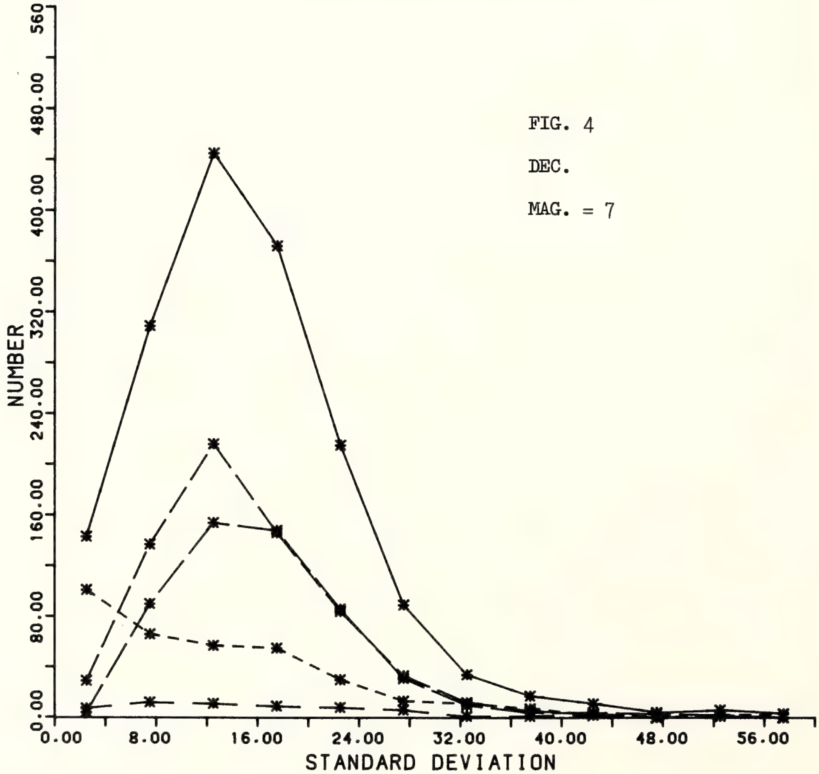
FIG. 4
DEC.
MAG. = 7
NUMBER
STANDARD DEVIATION

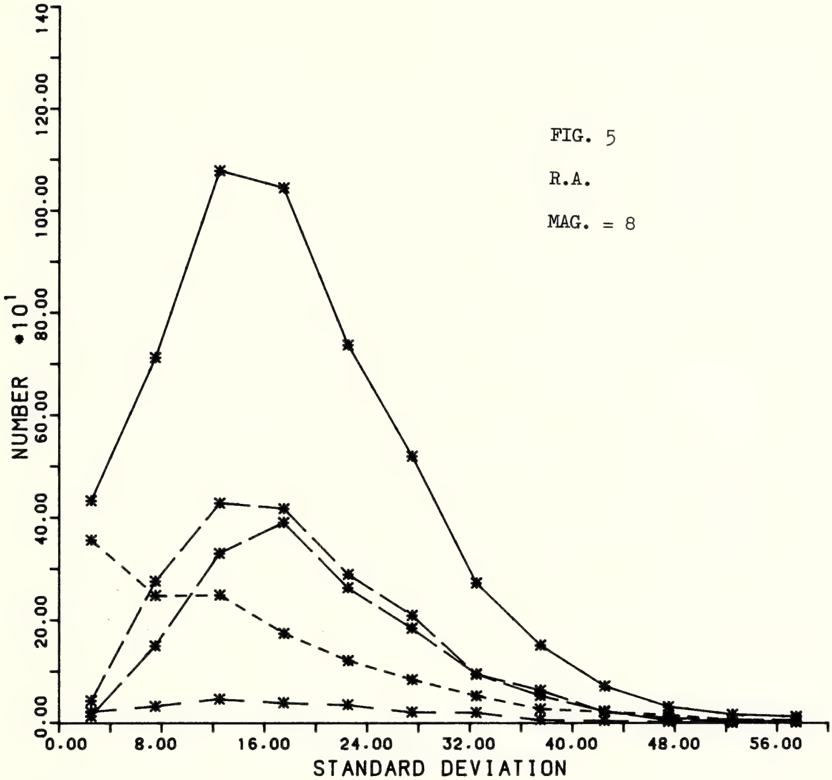
FIG. 5
R.A.
MAG. = 8
NUMBER *10¹
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
STANDARD DEVIATION

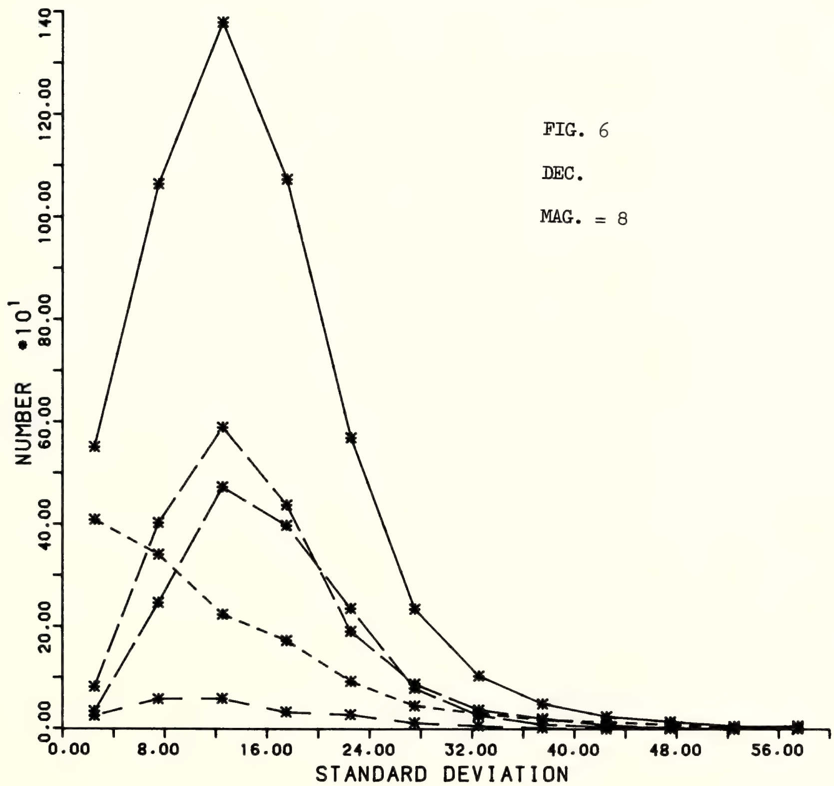
FIG. 6
DEC.
MAG. = 8
NUMBER *10¹
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
STANDARD DEVIATION

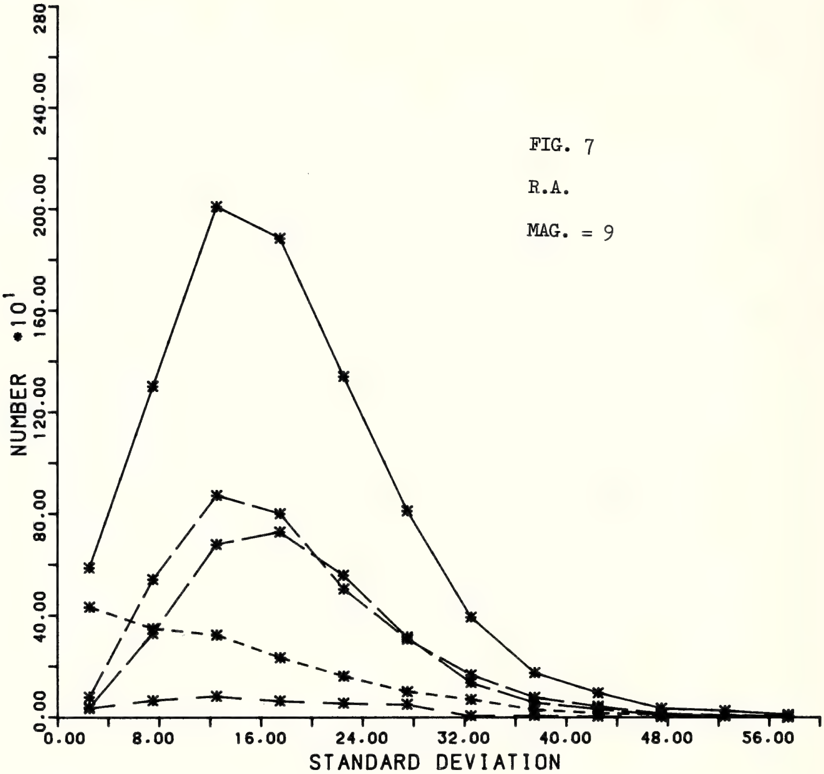
FIG. 7
R.A.
MAG. = 9
NUMBER *10[1]
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
STANDARD DEVIATION

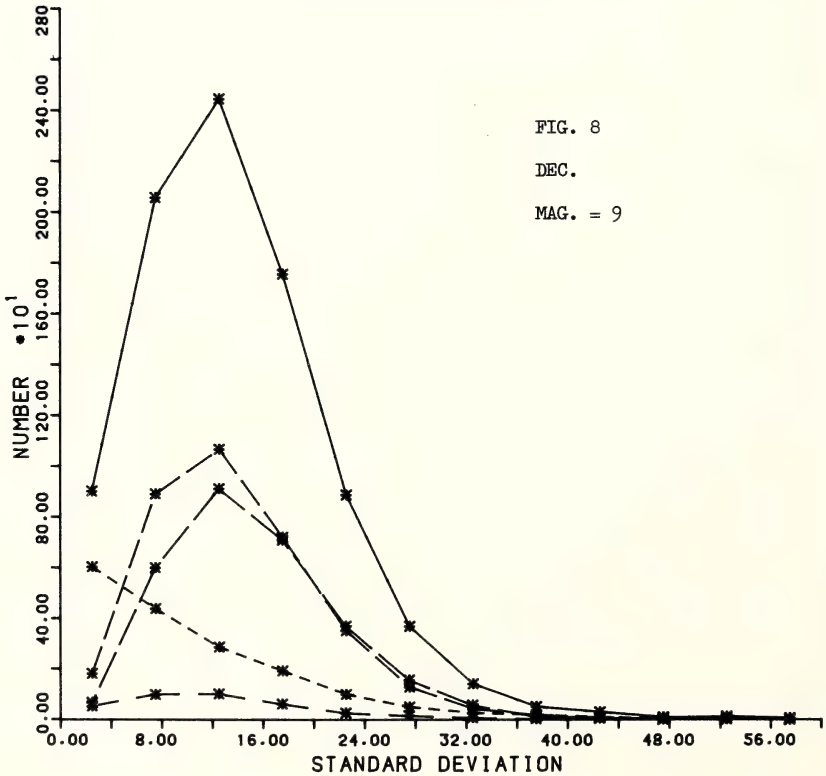
FIG. 8
DEC.
MAG. = 9
NUMBER *10[1]
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
STANDARD DEVIATION

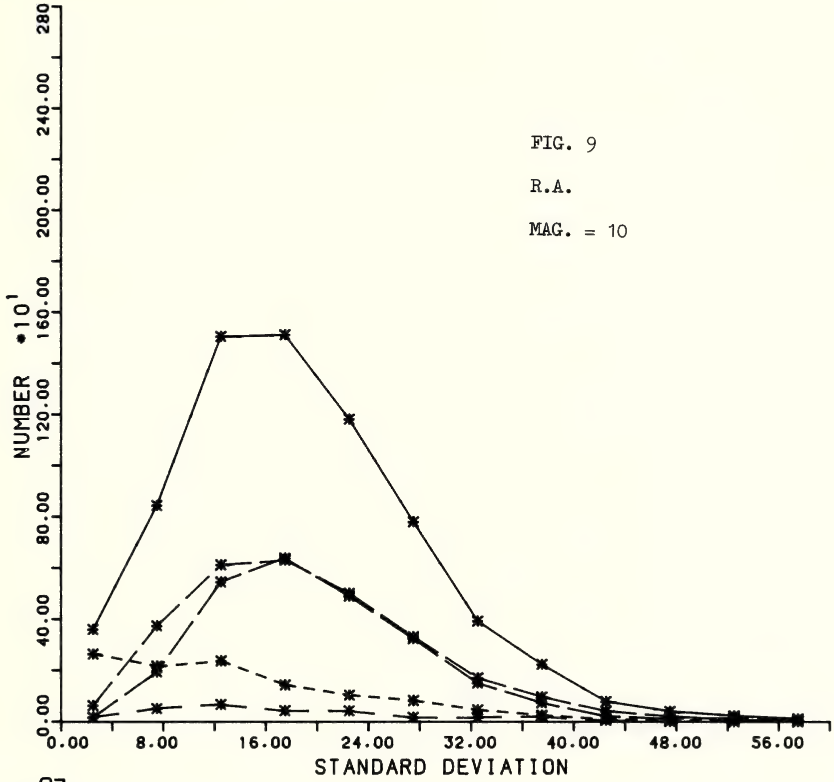
FIG. 9
R.A.
MAG. = 10
NUMBER *10[1]
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
STANDARD DEVIATION

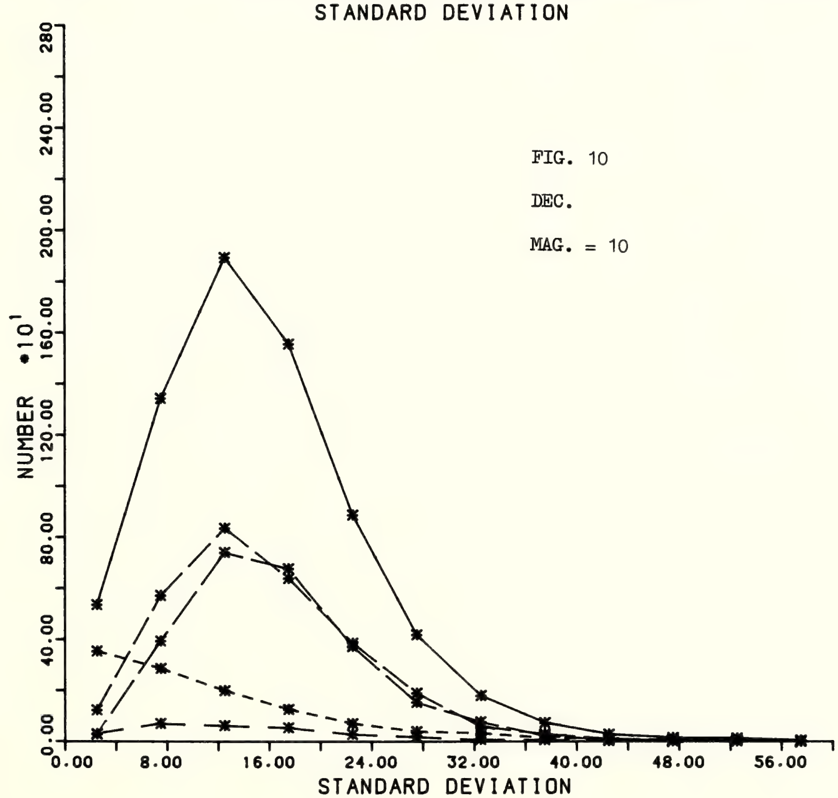
FIG. 10
DEC.
MAG. = 10
NUMBER *10[1]
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
STANDARD DEVIATION

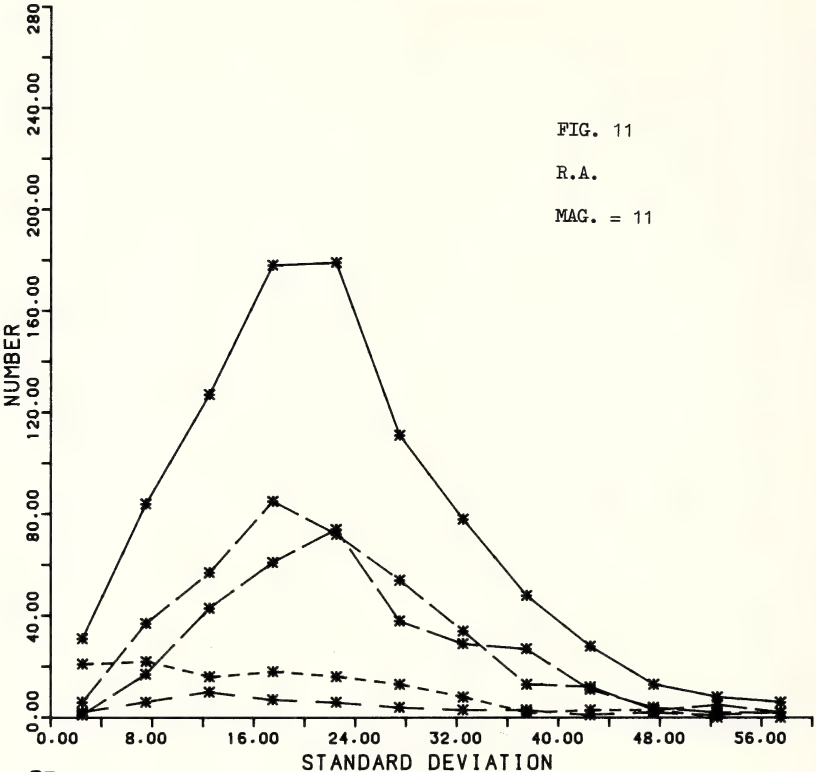
FIG. 11
R.A.
MAG. = 11
NUMBER
STANDARD DEVIATION
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00

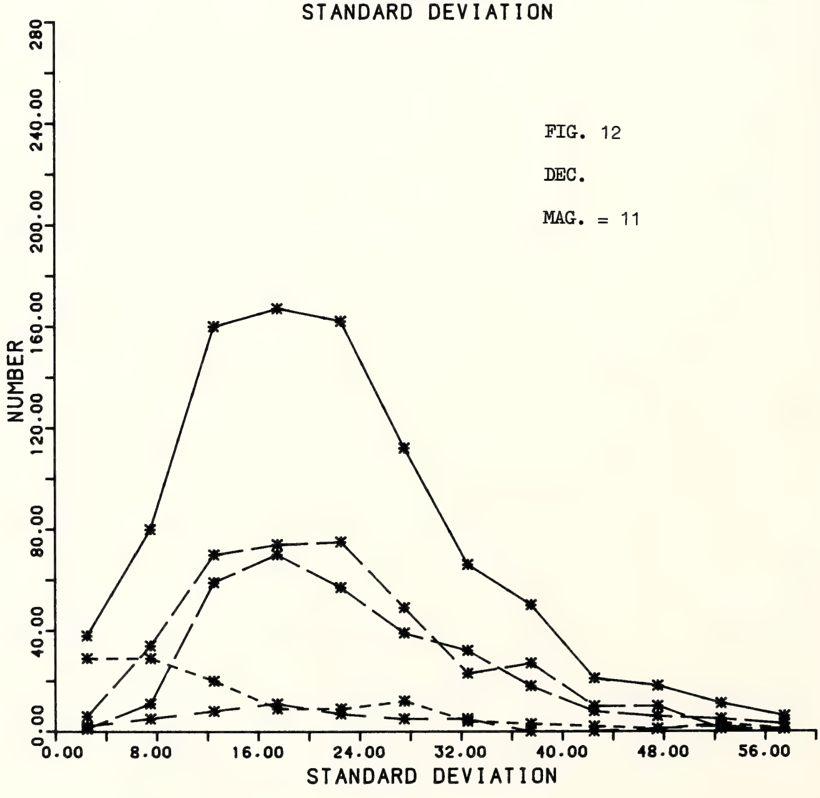
FIG. 12
DEC.
MAG. = 11
NUMBER
STANDARD DEVIATION
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00

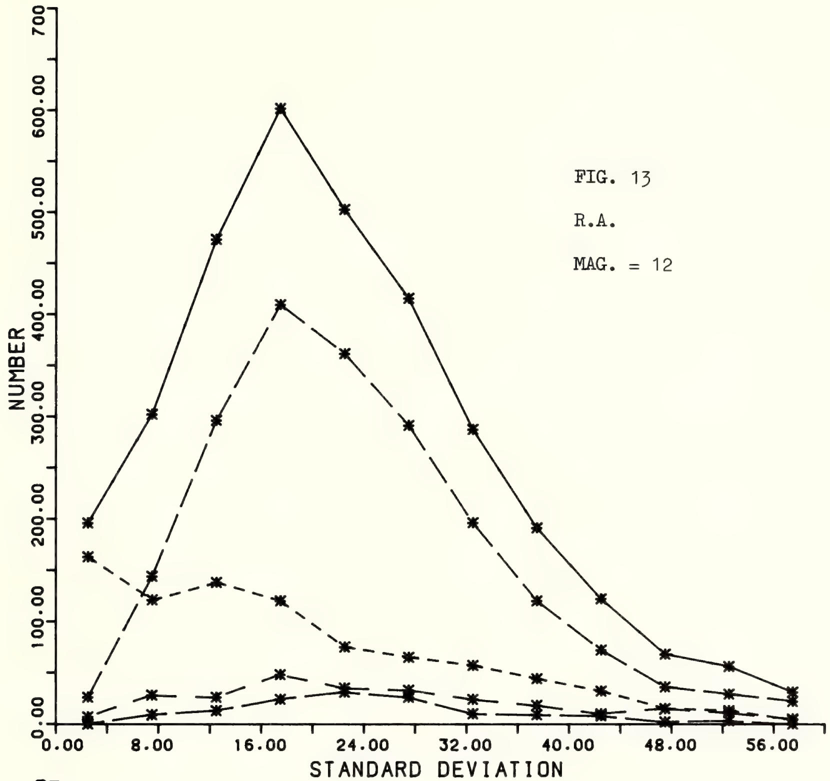
FIG. 13
R.A.
MAG. = 12
NUMBER
0.00
100.00
200.00
300.00
400.00
500.00
600.00
700
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
STANDARD DEVIATION

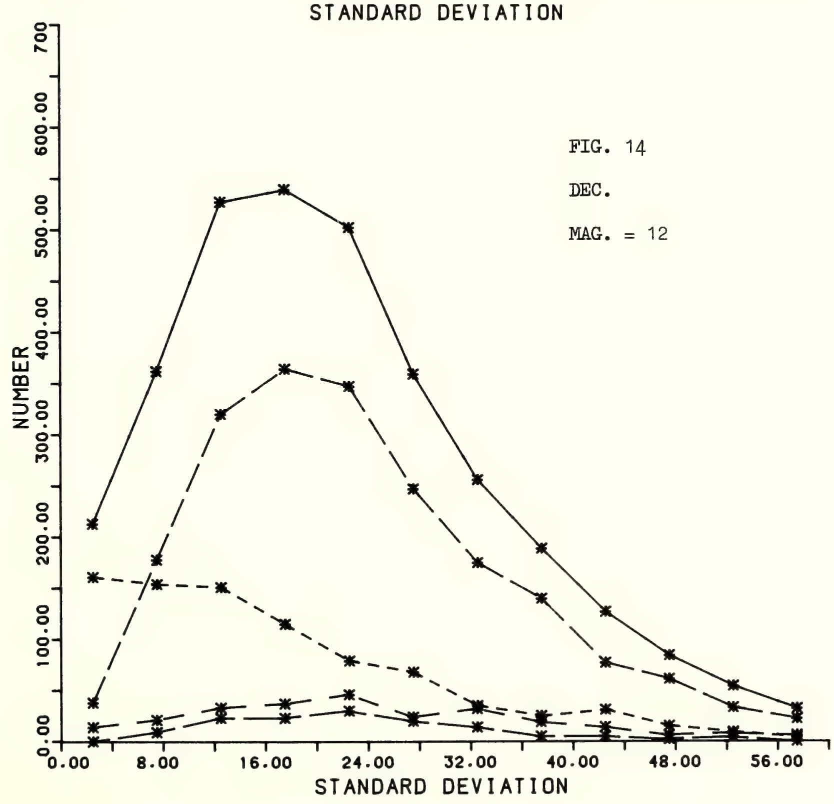
FIG. 14
DEC.
MAG. = 12
NUMBER
0.00
100.00
200.00
300.00
400.00
500.00
600.00
700
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
STANDARD DEVIATION

PROPER MOTIONS

First epoch positions for calculating proper motions were taken from the catalogues from which the stars were selected. Stars from the ZC catalogue were precessed from 1900 to 1950 while the stars from the GC catalogue were taken back from epoch 1950 to their original epoch, using the proper motions in the GC. None of the catalogues are in the FK4 system and so they had to be converted to that system. ZC stars were first reduced to the system of the GC using the tables given in the GC. Next, the ZC and GC stars were reduced to the FK3 system using Kopff's (1939) tables. Finally, the tables "FK4-FK3" published in the FK4 were used to reduce the ZC, GC and CPC stars to the FK4 system. No interpolation was applied during any of these conversions.

Proper motions were calculated using the formulae

$$\mu = (\alpha_2 - \alpha_1) / (t_2 - t_1) \qquad \mu' = (\delta_2 - \delta_1) / (t_2 - t_1)$$

where α_1 , δ_1 and t_1 are the first epoch right ascension, declination and epoch, respectively and α_2 , δ_2 and t_2 are the SSSC right ascension, declination and epoch, respectively. An epoch of 1903.0 was assumed for the GC and ZC stars. All large values of $\alpha_2 - \alpha_1$ and $\delta_2 - \delta_1$ were examined to see if the cause was a large proper motion or an error in the first epoch catalogue position or in the SSSC. A number of errors in the CPC were found in this way. These are listed in Table 6 along with some errors found at earlier stages of the preparation of the SSSC.

TABLE 6

ERRORS IN THE CPC

	IDNO				
On Magnetic Tape Only					
	603657	should be	$-53^{\circ}49'41''.8$	not	19'
	603682	epoch	38.2	not	68.2
	702797	should be	$-59^{\circ}51'01''.3$	not	$10''.3$
	703264	should be	$11^{h}00^{m}01^{s}.15$	not	10^{h}
	704462	should be	$-58^{\circ}10'05''.6$	not	$00''.6$
	705050	should be	$-59^{\circ}53'22''.2$	not	33'
	707236	should be	$-59^{\circ}02'25''.7$	not	22'
In Printed Catalogue					
	609032	should be	$-53^{\circ}45'34''.6$	not	43'
	700627	should be	$2^{h}20^{m}53^{s}.20$	not	$50^{s}.20$
	700761	should be	$-56^{\circ}42'02''.0$	not	41'
	700961	should be	$-56^{\circ}39'22''.2$	not	$59^{\circ}36'$
	702141	should be	$8^{h}06^{m}26^{s}.97$	not	$27^{s}.97$
	706946	should be	$-56^{\circ}09'47''.8$	not	59°
	707615	should be	$-58^{\circ}54'33''.5$	not	$13''.5$
	802809	should be	$-60^{\circ}31'49''.1$	not	51'

The proposed corrections have been checked against the CPD positions. As well as errors in the printed catalogue, a number of errors were found which only appear on the magnetic tape version of the CPC. These are also listed in Table 6. A comparison was also made between the new proper motions and the proper motion, if published, in the GC, ZC or the CPC. Ignoring cases where the published value is much higher than in the SSSC, as these are likely to be spurious, a number of cases remain where the SSSC value is much larger than that in published catalogues. These are listed in Table 7.

TABLE 7

PROBLEM STARS

IDNO	SSSC PROPER MOTION		PUBLISHED PROPER MOTION*	
	μ (in units of $0^{s}.0001$/yr)	μ' (in units of $0''.001$/yr)	μ (in units of $0^{s}.0001$/yr)	μ' (in units of $0''.001$/yr)
513281	205	-314	(-13)	(-8)
514488	278	-10	(4)	(-19)
604954	-327	-7	-5	8
703166	-247	5	88	-4
704322	-181	-4	121	-2
706921	-442	-35	59	-27
706953	33	-157	31	62
707400	380	-42	(-37)	(16)
801445	151	-217	3	10

*from CPC except for values in brackets which are from ZC or BPM.

The mean differences and the root mean square of the differences between the SSSC proper motions and the CPC proper motions (converted to the FK4 system) were calculated for those stars which had CPC proper motion. The results, subdivided on the basis of the size of the CPC proper motion are given in Table 8.

TABLE 8

COMPARISON BETWEEN SSSC AND CPC PROPER MOTION

	$\mu_s - \mu_c$ (in units of $0^s.0001$/yr)				$\mu_s' - \mu_c'$ (in units of $0''.001$/yr)		
	mean	rms	number		mean	rms	number
$0<\lvert\mu_c\rvert< 50$	-1.1	25.6	14362	$0<\lvert\mu_c'\rvert< 50$	-3.7	20.9	15274
$50<\lvert\mu_c\rvert<100$	4.3	43.3	1874	$50<\lvert\mu_c'\rvert<100$	-1.3	34.9	1231
$100<\lvert\mu_c\rvert<150$	-1.7	44.0	400	$100<\lvert\mu_c'\rvert<150$	-3.3	31.5	253
$\lvert\mu_c\rvert>150$	0.3	53.6	290	$\lvert\mu_c'\rvert>150$	-6.8	44.8	168

As shown in the table there is a considerable increase in the rms difference as the CPC proper motion increases. A likely explanation is that the higher the value for the proper motion, the more likely it is to be spurious. The mean difference for the majority of stars with low values of CPC proper motion is small, $-0^s.00011$ in right ascension and $-0''.0037$ in declination.

The uncertainties in the proper motions vary for each star dependent on the position uncertainty in the first epoch catalogue and in the SSSC as well as the difference in epoch. An average value can be calculated for stars from each catalogue. The formula used is

$$\sigma_\mu = (\sigma_2^2 + \sigma_1^2)^{\frac{1}{2}} / (t_2 - t_1)$$

where σ_1 is the standard deviation of the position at the first epoch t_1 and σ_2 is the standard deviation of the position in the SSSC at epoch t_2. Adopting a representative value for the SSSC of $\sigma_2 = 0''.10$ and $\sigma_1 = 0''.5$ for the ZC, $\sigma_1 = 0''.2$ for the GC, $\sigma_1 = 0''.17$ for CPC $52^\circ - 56^\circ$ and $\sigma_1 = 0''.14$ for CPC $56^\circ - 64^\circ$ we obtain

for ZC stars	$\sigma_\mu = 0''.008$ or $0^s.0009$	per year
for GC stars	$\sigma_\mu = 0''.003$ or $0^s.0003$	per year
for CPC 52°-56°	$\sigma_\mu = 0''.007$ or $0^s.0008$	per year
for CPC 56°-60°	$\sigma_\mu = 0''.007$ or $0^s.0009$	per year
for CPC 60°-64°	$\sigma_\mu = 0''.007$ or $0^s.0010$	per year

The proper motions for the 13 stars taken from the IRS are taken directly from that catalogue.

TAPE AND MICROFICHE DESCRIPTIONS

There are two machine readable tapes available to prospective users. Both tapes are available for the cost of the tape plus postage. The tapes are at present 9 track, 1600 bpi, labelled in EBCDIC format. Other formats may be arranged if necessary.

The tapes are known as the Sydney Southern Star Catalogue (SSSC) and Sydney Measured Positions (SMP). The SSSC is intended for all users of the positional and proper motion data. The SMP is only useful for users who wish to repeat the reductions using a different reference star catalogue, for example, the final version of IRS, or wish to use the full plate overlap method to re-evaluate the positions. Copies of both tapes have been sent to the Centre des Donnes Stellaires in Strasbourg, France, the Astronomisches Rechen-Institut in Heidelberg, West Germany and the Department of Astronomy, University of Florida in Florida, U.S.A.

The microfiche version of the SSSC appears essentially the same as the tape version except the right ascensions and declinations appear in their usual formats.

Sydney Southern Star Catalogue

This tape and microfiche catalogue consists of 26926 records. The first 23287 records are in right ascension order of stars between declinations $-51^\circ 00'$ and $-63^\circ 30'$. The next 3244 records in right ascension order are of faint Sydney Astrographic Catalogue stars presumed to be in the photographic magnitude range 11.0 to 11.5, although they are all designated magnitude 12.00. The last 395 records in right ascension order are of the stars south of declination $-63^\circ 30'$ that were primarily used as reference stars. The first four records appear below with their corresponding column headings and column limits marked:-

IDNO	MAG	R.A.	DEC.	EPOCH	N	MUA	MUD
700001	943	9755	20541594	69445	5	12	-4
700002	927	10128	20848319	69445	5	-31	-20
700003	997	20475	21261539	70087	5	107	-2
800001	997	22928	22734208	71314	5	-26	-19

IDNO This six digit identification number is a unique number for each distinct star. The first digit indicates the origin of the identification number displayed in the following table.

First digit of IDNO	Catalogue
1	Sydney Astrographic Catalogue (AC)
3	International Reference Stars (IRS)
4	Albany General Catalogue (GC)
5	Cape Zone Catalogue for 1900 (ZC)
6	Cape Photographic Catalogue for 1950 (CPC), Zone -52^{o} to -56^{o}
7	Cape Photographic Catalogue for 1950 (CPC), Zone -56^{o} to -60^{o}
8	Cape Photographic Catalogue for 1950 (CPC), Zone -60^{o} to -64^{o}
9	Cape Photographic Catalogue for 1950 (CPC), Zone -64^{o} to -68^{o}

For Sydney Astrographic Catalogue stars, the second digit indicates the declination zone in which it lies. The zones are designed as follows:-

Second digit of IDNO for AC stars	Zone
0	$-51^{o}00'$ to $-53^{o}30'$
1	$-53^{o}30'$ to $-56^{o}00'$
2	$-56^{o}00'$ to $-58^{o}30'$
3	$-58^{o}30'$ to $-61^{o}00'$
4	$-61^{o}00'$ to $-63^{o}30'$
5	$-63^{o}30'$ to $-66^{o}00'$

The remaining four digits for the AC stars were allotted sequentially in right ascension order for each zone. It is hoped that in future these numbers will be cross-referenced with the original AC numbers and plate centres. The remaining five digits for the other catalogues simply make up the identification number given to the star in the relevant catalogue.

MAG This four digit number gives the photographic magnitude in units of 0.01 of a magnitude. All the AC stars are given MAG equal to 1200 even though their true photographic magnitude should lie in the range 11.0 to 11.5. The remaining stars have their photographic magnitude as it appears in its relevant catalogue. As previously indicated, some photographic magnitudes were not present in the CPC and had to be derived from the visual magnitude using the spectral type.

R.A. The right ascension as an eight digit number in units of 0.001 seconds of time. The equinox is 1950 and the reference system used was Washington El Leoncito 1950. On microfiche the right ascension is in hours, minutes and seconds.

DEC. The absolute value of the declination as an eight digit number in units of 0.01 seconds of arc. The equinox is 1950 and the reference system used was Washington El Leoncito 1950. On microfiche the declination has the correct sign and is in degrees, minutes of arc and seconds of arc.

EPOCH This five digit integer gives the epoch of the position in units of 0.001 years after 1900.

N Gives in one digit the number of plates which were used to give the right ascension, declination and epoch. It ranges from two to eight.

MUA Five digit proper motion in right ascension in units of 0.0001 seconds of time per year.

MUD Five digit proper motion in declination in units of 0.001 seconds of arc per year.

Sydney Measured Positions

For those few users who wish to use it, the tape has a plate by plate format. The records for each plate are kept separate and are preceded by a plate heading and the plate constants. The plate heading has the following information:-

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1024	-5330	409	16	18	0	187	188	0	5003	1967296	10257	73	204	450	-1

A Right ascension of the plate centre, the first two digits being the hours and the last two being the minutes.

B Declination of the plate centre, the first three digits being the degrees and the last two being the minutes of arc.

C Total number of stars on the plate.

D Number of faint AC stars north of the declination centre.

E Number of faint AC stars south of the declination centre.

F Number of non-faint stars north of $2^{\circ}30'$ north of the declination centre.

G Number of non-faint stars with declinations between $2^{\circ}30'$ north of the declination centre and the declination centre.

H Number of non-faint stars with declinations between $2^{\circ}30'$ south of the declination centre and the declination centre.

I Number of non-faint stars south of $2^{\circ}30'$ south of the declination centre.

J Plate number.

K Epoch of the plate in units of 0.001 years.

L Barometric pressure in millibars of the time of exposure.

M Percentage relative humidity at the time of exposure.

N Temperature at the time of exposure in units of 0.1 degrees Celsius.

O The telescope focus setting at the time of exposure.

P The hour angle at the middle of the exposure in minutes West.

Following the plate headings are two lines of 5 plate constants each, which are for a plate constant solution of the form:-

$$\xi - x = ax + by + c + px^2 + qxy$$
$$\eta - y = -bx + dy + e + pxy + qy^2$$

These constants can be read in Fortran with the format 10E14.8 For example:-

```
 .14164122E-03  .24046714E-02  .14442351E+00 -.34047301E-06 -.18221255E-06
-.24046714E-02  .15413496E-03 -.10739198E+00 -.34047301E-06 -.18221255E-06
```

Then each image on the plate has a record with the following measurement data:-

IDNO IBS R.A. DEC. X Y MAG.

The IDNO, R.A., DEC. and MAG. all have the same meaning as for the Sydney Southern Star Catalogue. The additional data is:-

IBS The star type register.
0 : No side images were measured and the star was not used as a reference star.
1 : The central image measurement and the star was not used as a reference star.
2 : The average of the two side image measurements and the star was not used as a reference star.
5 : No side images were measured and the star was used as a reference star.
6 : The central image measurement and the star was used as a reference star.
7 : The average of the two side image measurements and the star was used as a reference star.

X,Y The seven digit measured average x,y coordinates of the image in units of 0.1 microns with (1000000, 1000000) representing the plate centre.

ACKNOWLEDGMENTS

We wish to thank the previous astronomers at Sydney Observatory who initiated this project, namely Dr. H. W. Wood, W. H. Robertson and K. P. Sims. Other Observatory staff who helped with the measuring and typing were Mrs A. Brown, Miss E. Burdis, Ms. J. Garland, Miss R. Skeers, Miss D. Teale and Miss J. Westaway. We would also like to thank Dr. R. Hunstead of Sydney University who assisted in the repair of the plate measuring machine at a crucial stage in the completion of the $-63^{\circ}30'$ zone, Mr. P. Halasz of the

University of N.S.W. who provided considerable assistance with microcomputer software and hardware and Dr. C. de Vegt of Hamburg Sternwarte who helped in determining the reduction scheme.

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Stoy, R.H. 1966. Cape Photographic Catalogue for 1950.0. *Ann. Cape Obs. vol 21, -64° to -80°.*

CPD Gill, D. and Kapteyn, J.C. 1897-1900. Cape Photographic Durchmusterung, Parts II-III. *Ann. Cape Obs., vol 4, -38° to -52°; vol 5, -53° to -89°.*

GC Boss, B. 1937. General Catalogue of 33,342 Stars for the Epoch 1950, vols 2-5. *Carnegie Inst. Washington, publ, no. 468.*

ZC Gill, D. and Hough, S.S. 1923. Zone Catalogue of 20,843 Stars, Equinox 1900. *Royal Obs., Cape of Good Hope.*
Spencer Jones, H. and Jackson, J. 1936. Proper motions of Stars in the Zone Catalogue of 20,843 Stars, 1900. *Royal Obs., Cape of Good Hope.*

FK4 Fricke, W. and Kopff, A. 1963. Fourth Fundamental Catalogue. *Veröff. Astron. Rechen-Inst. Heidelberg, No. 10.*

AC Nangle, J. and Wood, H.W. 1925-1971. Astrographic Catalogue 1900.0 Sydney Section *vols 1-53.*

PERTH 70 Høg, E. and Von Der Heide, J. 1976. Perth 70 A Catalogue of Positions of 24900 stars. *Abhandlungen Aus Der Hamburger Sternwarte vol 9.*

BPM Luyten, W.J. 1937. Bruce Proper Motion Survey. The General Catalogue *vols 1-2.*

IRS For details see: Scott, F.P. 1962. Status of the International Reference-Star Programs. *Astron. J.* 67 *p690.*

WL50 On magnetic tape only, courtesy of USNO. For details see: Smith, C. 1978. Some results of Observations with the Scott seven-inch Transit Circle at Leoncito. *IAU Coll.* 48, *Modern Astrometry, p447.*

SPC Eichhorn, H. 1983. Catalogue of 20457 Star Positions Obtained by Photography in the Declination Zone -48° to -54°. *Astron. J.* 88 *p546.*

General

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(Manuscript received 26.10.1983)

Journal and Proceedings, Royal Society of New South Wales, Vol. 116, pp. 71-76, 1983
ISSN 0035-9173/83/020071 — 06 $4.00/1

The Technological Revolution In Communications and Computing

T. W. Cole

ABSTRACT. The field of microelectronics and its main product the silicon chip (integrated circuit) are used to illustrate rapid advances being made in technology. In communications and computing changes are described which will have profound effects on society. Some of these are discussed in a world context. The main conclusion is that change must be considered inevitable.

INTRODUCTION

An address like this gives an all too rare opportunity to distance oneself from the intimate details of research and teaching, to step back, and to take an overall and sweeping view of the technologies with which one is concerned. One can attempt to place these technologies in both a world and an Australian context, and to reflect on the implications for the future. Yet even the title of the talk gives difficulties since the subject is an enormous one with wide ramifications. The concept of a technological revolution needs to be discussed before placing Australia in its context. To do this, one technology will be used to illustrate in detail the dramatic rate of technological advance which is occurring. The technology chosen is microelectronics whose main product is the integrated circuit- the 'silicon chip'. Developments in microelectronics will be seen to have had a profound effect on both computing and communications. Projections of this technology, its social impact, and specific consequences for Australia need then to be seen as a personal view, one coloured by an immersion in the rapid developments and one influenced by the need to arrive at an educational and social policy which will have relevance to an Australia of the year 2000 and beyond.

THE COMMUNICATIONS REVOLUTION

It is not possible to define exactly what is meant by a technological revolution. One can but draw on the day-to-day experiences of everyone to realise that the society is undergoing rapid and extensive change as technological developments modify our working habits, our recreation, and the way we look at the world around us. In a way indicative of the rapidity of change, one can reflect that it is not uncommon in Australia to have had grandparents already having migrated halfway around the world on months-long ship voyages when Marconi broadcast over the Atlantic. Yet only one lifetime later the point has been reached where, for example, photographs of the Earth taken from the Moon have coloured forever the attitude humans have of their own planet. Communication satellites and rapid air transport have removed the concept of isolation from the rest of the world that Australia might have experienced just that lifetime ago. Any change spreads rapidly over the globe accompanied by an inability on the part of society to put up the shutters in a vain attempt to shield that society from change. On another level, one can see developments in molecular biology and cosmology changing the moral and religious outlooks of us all. A demystification has occurred based on an increase in knowledge and on high technology applications of that knowledge. The rate of the change also increases and with it the spectre of an increasing gap between those communities with and those without these advances. The concept of the technological rich and the technological poor are of importance to Australia. The problem of identifying into which of these groups Australia falls is discussed below.

Six nations dominate world science and technology and hence world development. These are the USA, USSR, UK, Japan, West Germany, and France. Together these countries have the major part of the world's research- and development- manpower and contribute almost all of the World's research expenditure. The Third World has little of this manpower and is continuously losing it by emigration. The revolution as such is then in the European based civilisation and in Japan. The question to be addressed is:- where does Australia fit into the picture? Will the above mentioned countries be the countries to continue to lead? Who will inherit the fruits of the Technological Revolution?

AUSTRALIA IN A DEVELOPING WORLD

Australia clearly possesses a high level of development with modern communications on land, sea, and air as well as modern telecommunications. This has contributed to a coherent language, economy, culture and politics despite the distance barrier. Australia takes its place in the world scene of trade with its agricultural products, its minerals, its services and some selected manufactures. To place this standard of development in perspective, it is fruitful to talk in terms of the Gross National Product (GNP) per capita, i.e. the total amount a country earns per man, woman, or child in a country (Payne,1982). In 1788 the Industrial Revolution was beginning and Australia, like Britain at that time had a GNP/capita of $200, a sum which corresponds in real terms with the GNP/capita of today's India and China where

*Presidential address delivered before the Royal Society of New South Wales , 6th of April , 1983.

traditional cultures resisted the modern technologies. As early as 1860, Australia's GNP/capita was 50% above that of the UK and is now around $10 000 or 50 times that of the average Indian. It might be considered comforting that we are ahead of the world average which is about $2 000, but there is a gap of 40 times between rich and poor countries and the possibility exists that this gap may be broadening.

Australia is the 'lucky country' but the world scene is not static. There are developments of critical importance to Australia, as will be illustrated by consideration of Australia's trading patterns. About 80% of the trade goes to the advanced and rapidly developing nations of the Pacific with little to the Indian and Chinese nations. Trade has moved from the markets in Europe to the world's third largest economy - Japan. This country, along with Hong Kong and Singapore represent a new class of economy, low on resources but very high on rapid industrialisation. It is not often appreciated that the GNP/capita of Taiwan and of Korea have been growing at 10% per year for the last decade while that of Indonesia, Malaysia, Thailand and the Philippines have been growing at 5% for 20 years. Last year Australia's growth was essentially zero. These countries in the Pacific region are the markets of Australia with our exports to them having doubled and our imports from Europe having halved over the last 20 years.

Such a changing scene demands that Australia's market strengths must adapt in the face of the increasing competitiveness of these developing countries. Traditional low cost shipping, labour and tourism has been displaced while the middle technologies of steelmaking, shipbuilding, and the production of trucks,home appliances, shoes and clothing are more economical elsewhere. It is in selected areas of technology that our enterprise has at least some form of edge: scientific agriculture, scientific mineral exploration and exploitation, complex services, and high productivity manufacture can stand Australia apart. Australia stands apart also in another sense. The large distance to the markets of the world accentuates the penalties Australia pays in its export trade. A point will be made that knowledge is easily exported, certainly more easily than a tonne of coal or iron ore. The major factor in knowledge export is telecommunications.

EMERGENT TELECOMMUNICATIONS

Some key dates for telecommunications are 1944, 1947, and 1966. The first is the year in which Arthur C. Clarke proposed the concept of the geostationary satellite, the means to the provision of large bandwidth communication links around the world. In 1947 the first transistor was demonstrated in Bell Laboratories and it was only 13 years later that the first integrated circuit or IC or silicon chip was developed at the Fairchild company in the USA. The last of these dates, 1966, represents the work of Kao at the company ITT in putting forward the practical concept of optical fibres for cheap and wide bandwidth communications.

These apparently simple and recent developments have led to digital hardware, to the field of opto-electronics (photonics), to software, and to the converging fields of computers and communications. None of these technologies have matured yet, all are developing rapidly. It is impossible to project them far into the future without an understanding of the basic elements of the technology.

MICROELECTRONICS

At the base of all modern computing and communications is the field of microelectronics and its product the silicon chip. 'Microelectronics' has the literal meaning of electronics on a small scale. The scale is indeed small and is measured in microns or millionths of one metre. As Figure 1 indicates by comparison with a human hair, to say that the 'wiring' and transistors on a modern silicon chip can be finer than 1 micron in width means that one is dealing with astonishing compactness. Being able to compact circuitry to

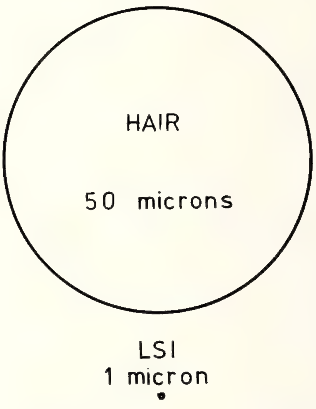

Fig. 1. To illustrate the small scales in microelectronics, the micron size of the features on an integrated circuit are shown against the size of a human hair.

this scale leads to enormous complexity. The source of the power of microelectronic processing lies in the fact that a silicon chip is fabricated by a sequence of similar steps 'printing' different geometrical patterns as successive layers on the slice of silicon crystal which forms the substrate of the device. Figure 2 shows by example just one corner of a design. The relative positioning of the diffusion, polysilicon, 'cuts', metal, and implant layers can create individual transistors and their interconnection in a straightforward sequence of operations. As the techniques of fabrication developed and as the necessary solid-state physics evolved, the maximum complexity which could be fitted into a single silicon chip grew. The rate of the growth can be illustrated by an analogy. The wiring on the individual silicon chip is considered analogous to the pattern of the streets criss-crossing a city. In 1963 the silicon chip was no more complex in its wiring pattern than the streets of a city centre, a complexity with which we can all cope. At that time the features were 25 microns in width and the overall chip was only 1 mm square. But by 1978 techniques had developed to the point where 5 mm square chips with features 5 microns wide could provide complexity corresponding to the

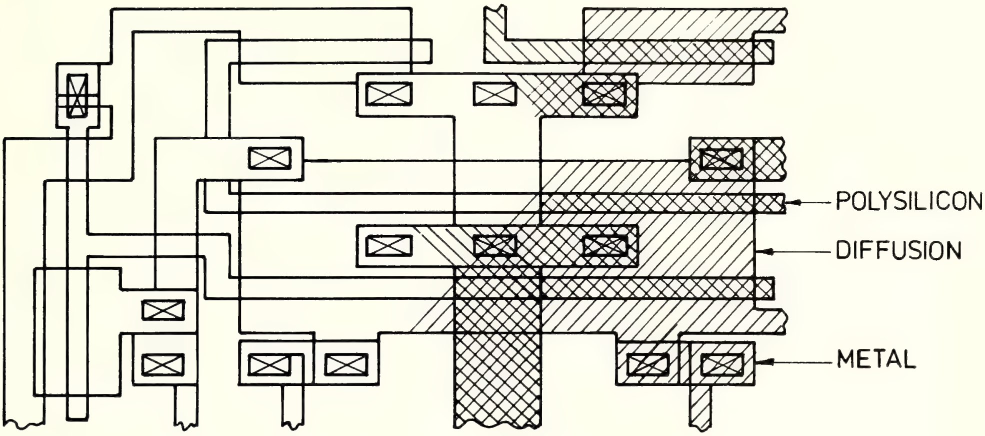

Fig 2. A small part of an integrated circuit layout shows the concept of a device made up of successive layers of differing geometrical arrangement. The nMOS process illustrated here has three main layers partially indicated by different hatchings. These would be metal, polysilicon and diffusion. A transistor is formed whenever the polysilicon path crosses an area of diffusion.

street pattern of the entire Sydney metropolitan area. It is rare to find even a taxi driver who can understand the complexity of that level of patterning. But work demonstrated in the laboratories tells us that the techniques are already established to produce, by 1985, chips 10 mm square with features of 1 micron width. This level of complexity is analogous to an area of the whole of New South Wales covered with a roadway pattern of the same density as central Sydney.

What of the future? The recognised fundamental limits lead one to wiring patterns of 0.1 micron width over even larger chips.The analogy would then reach the incredible stage of complexity of having the entire Australian continent covered with roads at the same density as central Sydney. There is absolutely no way that an individual could conceive of the intimate details of such complexity. But when appropriate new approaches developed specifically for the management of complexity are applied to the design of such devices, the raw complexity is capable of providing astonishing computing and processing power. Of some importance is the fact that such complexity is provided at lower and lower cost but with ever increasing reliability. It can only be designed and produced by using powerful computers as tools in the fabrication. The field of microelectronics is an iterative process in which its products are used as tools to help the development of even more powerful products.

The functionality which can be placed on a single chip has been doubling every year, while the cost per operation halves every two years. It is now possible to place approximately one million transistors on a single silicon chip. Had a similarly rapid development occurred in the car industry, it would have led to cars costing one dollar and needing service every 1 million kilometres. An alternative analogy is that passenger planes having as many as 500,000 passengers would be flying across the Atlantic with a fare of only 25 cents.

Elements of this story of development can be found in other technologies but few can match microelectronics in the speed at which key ideas and skills matured along developmental curves like those shown in Figure 3 (Mead,1981). It seems to be an historical fact that a subject will be first identified by one or two individuals and then follow a rapid development. Each subject then enters a period of maturity and stabilisation. The necessary technology for fabrication of the silicon chips has already reached the mature state. The skills needed to handle the complexity and to design a desired functionality into the silicon is developing rapidly. The application of the tremendous power of the devices is a young subject and will clearly have effects far beyond those we see now.

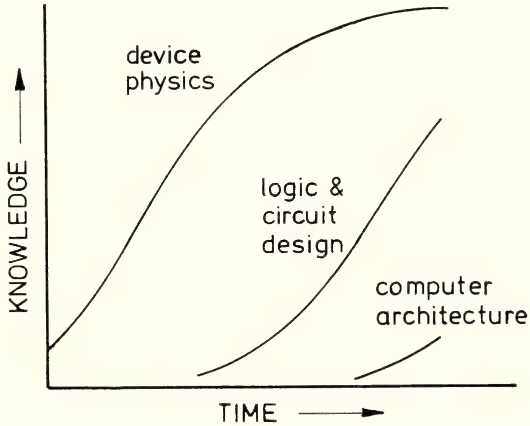

Fig 3. Any field of study can be argued as following development curves of the general form shown. The critical fields for integrated circuits are identified.

It has been said that by 1990, microelectronic circuitry will be of the same compactness as the circuitry of the human brain and that by the turn of the century computing capacity will pass the level of human capacity. Future directions lie in new architectures arranging this complexity as a myriad of interconnected processors each with their special function which, overall, provides a range and variety of activities far beyond that possible with a single processor. Such an architecture is essentially a communications system, a network of information transfer, held together as in all computer systems by software, the computer programme 'glue'.

Comparison with human capacity is appropriate: a number of nations pursue the development of a 'Fifth Generation Computer', to incorporate the concepts and ideas of artificial intelligence. The result is to be a system useable by the untrained, noncomputer person, programmable by the user, and able to converse with the user while jointly arriving at a workable computer solution to the problem at hand. Expert systems, voice synthesis, voice recognition, vision analysis are all there on the rising part of the development curves of Figure 3. Who dares to predict the scope of application and impact such developments will bring? Who still denies the existence of a new revolution?

DIGITAL COMMUNICATIONS

The developments in microelectronics have had a major impact on communications as it now takes advantage of the cheapness, reliability and flexibility of a digital approach. The Australian telecommunications network is changing to one based on the digital or computer concept and increasing use is being made of the facilities offered. There is a clear convergence between the areas of computing and communications, a convergence recognised now for some time but which has important ramifications for the teaching areas and the traditional compartmentalisation of subjects. The elements of this convergence are reinforced by a realisation that the largest computer system in the world is actually the Bell Telephone switching system. In the large telephone exchanges of that system, six million transactions take place in the busiest hour, and the reliability of the exchange is such that failures occur for only one thousandth of one percent of the time. This system is run by a huge computer programme which, for the entire Bell network, contains 18 million lines of instructions! Most computers are difficult to use but this particularly complex computer is actually used and accessed by over 200 million people using a rather simple computer terminal, the telephone (Ross,1982). It is this 'user-friendliness' which can now be incorporated in computing in a way which can bring processing power to all in ways still to be defined.

EDUCATION

Such rapid change, such potential for application, creates enormous difficulty in the definition of an optimum training programme for technologists whose working career will stretch into the next century. General outlines only can be given. It will always be necessary to have a broad and basic background in the sciences and mathematics but already one sees quite dramatic shifts in the type of science and mathematics relevent to the new areas of processing and communications. The availability of plentiful and cheap computing power has meant that this resource replaces the drawing board and the slide rule, even the pencil. The computer is the tool with which to handle the complexity of design. The level of complexity now is such that in several weeks of work a modern engineer can outstrip the complexity of an entire lifetime's output of an engineer of only a few years ago.

The pervasiveness of the technology and the breadth of the application of the products of the technology have other implications. One of these is the role of the technologies in national economics. Different countries have quite different priorities. For example,in the USA of every 10,000 citizens, 20 are lawyers, 40 are accountants, and 70 are engineers. The corresponding figures for Japan are 1 lawyer, 3 accountants and 400 engineers. In the USA 5 to 7% of the Bachelors' degrees are awarded to engineers whereas the corresponding figure for Japan is 20%. Such priorities and the products of the technology will have wide ranging effects.

EFFECTS ON OUR SOCIETY

The experience of the last 200 years can offer some insight into the effects the current changes might have on our society. There have been two main shifts in employment patterns during this time. Firstly, agricultural employment declined as the major employment sector. Its place was taken by employment in the newly establishing industrial area. Manufacturing industry underwent a continual rise between 1760 and about 1890. It became the dominent employment area for the 'modern' societies. This industrial era has been displaced now by the rapid rise from about 1930 to the present by employment in the 'services' areas such as administration, welfare, education and transport. Australia has a very high proportion of its workforce in this sector. The developments in technology and communications have a major impact on the service sector and its primary goal of information collection, collation, processing, storage and distribution. For example, several overseas reports predict dire employment shifts affecting the areas of insurance and banking over the next decade. For instance France will see 30 to 40% fewer 'jobs' of the current type in these areas during the above mentioned time span (Nora and Mine,1978). Similar conclusions could be expected for other countries. Projections can identify an advanced country as a Post-Industrial Society with highly productive and automated manufacturing and service industries requiring a far smaller employment base but one of much higher level of skill than in the past. The consequences indicate the need to find alternatives to the routine employment tasks which currently are the fate of most of our advanced societies. If leisure is to be the replacement, then one has an interesting departure from the leisured classes of the past who were invariably the upper and priviledged classes. One could predict a major part of the community being at leisure but a significant number of people still representing a highly skilled and long-

working elite. This elite copes with the complexity of the systems and will provide the productivity and services funding the leisure of the majority.

Displacement of both people and job opportunities has not been easy in the past. Study of the cotton mills of northern England and the industrial areas in central England shows the nineteenth century filled with much distress and trauma, relieved eventually by migration and alternative lifestyles. Not all societies have, however, been able to successfully navigate the change. Of some concern is that widening gap between rich and poor in the world, between those forming a part of the rapid changes and those outside change. The major question is to ask with which group is Australia aligning itself as the end of the century draws near.

EXPERIENCE OF THE PAST

The Industrial Revolution grew out of the Dark Ages of Western Europe and not out of the flourishing areas of civilisation of the Greeks, Arabs, Indians, or Chinese. A period of stagnation in the world had meant that little was added to the world store of knowledge and skills until well into the sixteenth century. Even after the Renaissance in Europe and well into the eighteenth century, China, India, and the Arabs could well have taken the initiative in establishing the industrial revolution but did not. Yet China had had for a long time the key developments on which an industrial society could develop. Gunpowder, metallurgy, paper, and the compass were the most critical elements. The Arabs had the accumulated knowledge of the Greeks and Romans as well as being close to the Renaissance changes in Europe. They had a large empire and had a well developed trading pattern. The Europeans acquired all the key elements of knowledge and skill via the Arabs but no-one other than the Europeans were able to appreciate the implications of change. The Indian, Chinese, and Arab societies were locked into rigid attitudes and ways. They were self-confident and arrogant in a way interestingly revealed in a letter from Emperor Ch'ien Lung of China to King George III of England in 1793 (Rajaratnam,1982). In it is shown the self-confident and arrogant manner of one blind of the changes occurring in the world around one.

"You, O King, live beyond the confines of many seas; nevertheless impelled by your humble desire to partake of the benefits of our civilisation, you have despatched a mission respectfully bearing your memorial....the earnest terms in which it is cast reveal a respectful humility on your part, which is highly praiseworthy.....

"If you assert that your reverence for our Celestial Dynasty fills you with a desire to acquire our civilisation.....(then) even if your envoy were to acquire the rudiments of our civilisation, you could not possibly transplant our manners and customs to your alien soil......

"Strange and costly objects do not interest me. I....have no use for your country's manufactures....Our Celestial Empire possesses all things in prolific abundance and lacks no products within its own borders. There is therefore no need to import the manufactures of outside barbarians in exchange for our own produce. But as the tea, silk and porcelain which the Celestial Empire produces are absolute necessities to European Nations and to yourselves, we have permitted, as a mark of favour, that foreign trading centres be established at Canton....so that your country (can) participate in our beneficience....

"Do not say that you were not warned in due time. Tremblingly obey and show no negligence."

The ruling classes were smug and had the wrong temperament and psychology. Europe on the other hand had no golden age to reflect on. Europe could look forward to change, to improving Man's lot in the world.

Of concern in Australia is that signs of the same stagnation, of the same reflection on a passing golden age is manifestly evident. Instead of silk, tea and porcelain it is wool, meat, iron ore and coal. Australia inherited the best of the Industrial Revolution and did much to look after the rights of man and woman, rights of free enquiry, of government by consent. Yet it is not at all clear that these are the values most appropriate to the task of judging the fruits of this new revolution.

Change needs to be looked on as a positive thing, something to be accepted with challenge, not just rejected on the basis of past situations. It also means that new bases to the generation and distribution of resources throughout our society need to be found. The consequences of failure to respond to this change could be severe. There are already identifiable countries around Australia without the encumbrance of a golden past who have accepted the challenge, who are diminishing the gap between the rich and their own poverty. The gap between rich and poor will widen, with new definitions of who is rich and who is poor.

CONCLUSIONS

The technological revolution in communications and computing is important. It is an important factor in the re-shaping of our society. It can be a major factor in the way our future resources are created. It can be one way of absorbing the displaced workers from the industries of the past era.

In education, is seen a major need to inject this attitude of adventure and challenge, to pursue with confidence these new technologies. The graduate needs a solid basic training on which to build. But the realisation is emerging that a spirit of adventure and confidence is just as important. It is a frightening prospect to think of one's children growing up in a country being left on a downward slide by nations who have accepted the challenges of the technological revolution.

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Journal and Proceedings, Royal Society of New South Wales, Vol. 116, pp. 77-103, 1983
ISSN 0035-9173/83/020077 — 27 $4.00/1

Restite, Xenoliths and Micrograniitoid Enclaves In Granites*

R. H. Vernon

ABSTRACT. Microstructural evidence of restite is meagre or absent in high-level metaluminous (I-type) granitoid plutons, and is limited in high-level peraluminous (S-type) granitoids. The microgranitoid enclaves (autoliths, "cognate xenoliths") that occur abundantly in both metaluminous and peraluminous granitoids are probably formed by quenching of magma in the plutonic environment. The enclaves are best explained by mingling and quenching of globules of more mafic magma in the host granitoid magma, although some may be solid fragments of quenched magma. Several quenching processes are feasible, provided incorporation of partly liquid material is postulated. However, mineralogical and microstructural evidence of hybridism suggests that many microgranitoid enclaves may be the result of magma mixing, either in the same reservoir as the host granitoid or elsewhere. Mingling of magma blobs with the granitoid magma is consistent with all the characteristic features of microgranitoid enclaves.

INTRODUCTION

The honour that attends an invitation to deliver the Clarke Memorial Lecture is intensified for me by the fact that four of my teachers have been so honoured. They are A.H. Voisey, K.S.W. Campbell and J.F.G. Wilkinson, who taught me at the University of New England, and the late A.B. Edwards, who continued my education at the C.S.I.R.O.

For the last four years, R.H. Flood and I, assisted by W.F. D'Arcy, have been investigating granitoid microstructures at Macquarie University. Many of our specific results have been published or soon will be (e.g., Flood & Vernon, 1979; Vernon & Flood, 1982; Vernon *et al.*, 1983). This lecture is partly an extension of our published work on the evidence for restite in graintoid rocks and partly a presentation of my own ideas on the nature and origin of micrograintoid enclaves (autoliths, "cognate xenoliths"). First, I examine the microstructural evidence for restite in high-level graintoid plutons, concluding that generally it is absent, weak or limited. Then I discuss the origin of "microgranitoid enclaves", concluding that they are not of restite origin, as has been suggested, but that they result from quenching of magma in the plutonic environment. Finally, I suggest that magma mingling may be the best way of forming the enclaves, although other processes may also contribute.

THE RESTITE HYPOTHESIS

The "restite hypothesis" for the development of granitoid suites (Bateman *et al.*, 1963; Piwinskii, 1968; Presnall & Bateman, 1973; Wyllie *et al.*, 1976; Wyllie, 1977; White & Chappell, 1977; Chappell, 1978) holds great sway at present, especially in Australia, but also in some quarters overseas. Excellent field, chemical and isotopic investigations, especially in eastern N.S.W. (e.g., Chappell, 1978; White *et al.*, 1977; Hine *et al.*, 1978; Griffin *et al.*, 1978; Shaw & Flood, 1981), have revealed the existence of suites of related granitoid plutons in high-level batholiths, and that some of the chemical variations within and between related plutons are commonly linear. This linear variation implies that mixing may have dominated over crystal fractionation (Harker, 1909). The restite hypothesis explains the linear variation by progressive unmixing of restite (unmelted solid residue) brought up with felsic "minimum melt" from the source area ("restite unmixing"). However, in my opinion, much of the microstructural evidence relevant to the restite hypothesis has been misinterpreted or minimized, in favour of chemical evidence, and so this paper deals with microstructures in some detail. As stated by White (1983, p.992), "we have too long ignored simple petrography and relied only on geochemistry to solve our problems".

The concept underlying the restite model is that "the products of partial melting (both melt and restite) can move upwards, en masse, to form granitoid plutons or volcanic rocks" (White & Chappell, 1977, p.8). This is really an assumption at this stage, much depending on the ratio of melt to residue, the viscosity of the melt, and doubtless other factors, but this problem is outside the scope of this lecture.

In the extreme application of the restite hypothesis, phenocrysts in volcanic rocks have been regarded as modified restite. For example, Wyborn *et al.* (1981, pp.10341-2) contended that all phenocrysts (quartz, plagioclase, biotite, garnet, orthopyroxene and cordierite) in peraluminous volcanic rocks of the Hawkins Suite in the Lachlan Fold Belt, S.E. Australia, are of restite origin, presumably modified by overgrowths precipitated from the melt, to produce the observed euhedral shapes. This interpretation, if accepted, alters the traditional view of volcanic rock microstructures. Normally petrologists regard uniformly dispersed, euhedral phenocrysts in

* *Clarke Memorial Lecture; delivered 21 September, 1983.*

volcanic rocks, occurring, as they do, in rocks of ultramafic to felsic composition, as products of magmatic crystallization under conditions of slow rates of homogeneous nucleation at small degrees of undercooling. Furthermore, the supposed restite phenocrysts are consistently isolated from each other, whereas much of the material inferred to be restite in granitoids (e.g., the mafic aggregates referred to later) and in extrusive rocks (e.g., Flood *et al.*, 1977) occurs in aggregates. However, interpretations of restite grains completely converted to igneous-looking crystals by magmatic reactions are difficult to disprove by using microstructural evidence.

Presumably phenocrysts of plagioclase in basalts are exempt from the interpretation of Wyborn *et al.* (1981), since plagioclase is not a stable mineral in the source rocks. Furthermore, the experiments of Green (1976) and Clemens & Wall (1981) have shown that cordierite, orthopyroxene, almandine-rich garnet and biotite can crystallize from the melt in peraluminous granitic magmas, confirming the microstructural interpretation of Brammall & Harwood (1923, 1932) and the recognition of White and Chappell (1977, p.18) that euhedral cordierite and some garnet in peraluminous granitoids may be magmatic. In view of these considerations, the extreme interpretation of Wyborn *et al.* (1981) is highly questionable.

MICROSTRUCTURAL EVIDENCE OF RESTITE IN GRANITOIDS

Microstructural evidence commonly advanced for the presence of restite in granitoid plutons consists of (1) mafic aggregates ("clots"), (2) corroded plagioclase cores, and (3) dark enclaves or "xenoliths" (Presnall & Bateman, 1973, p.3197; White & Chappell, 1977; Pitcher, 1979, p.635). I will consider each of them. Restite should tend to equilibrate with the melt as the magma rises (White & Chappell, 1977, p.18), so that, in theory, microstructural evidence for restite tends to be progressively removed. However, examples of partly equilibrated restite are commonly cited, and so these at least must be evaluated.

Mafic Aggregates

Presnall & Bateman (1973, p.3197) and Chappell (1978, p.274) contrasted separate, euhedral crystals of hornblende and biotite with anhedral grains of the same minerals in aggregates ("clots") in metaluminous granitoids of the Sierra Nevada, U.S.A. and southern New England, N.S.W., suggesting a restite origin for the clots. Similarly, White & Chappell (1977, p.17) interpreted euhedral crystals of hornblende in the non-minimum melt Jindabyne Suite, N.S.W., as being magmatic, presumably in contrast to the supposedly minimum melt Moruya Suite. However, I have observed euhedral hornblende in the Tuross Head Tonalite of the Moruya Suite. So evidently only some of the mafic material, even in supposedly minimum-melt suites, conceivably could be interpreted as restite.

White & Chappell (1977, p.11) inferred that pyroxene cores in amphiboles in some metaluminous (I-type) granitoids represent restite (granulite facies) pyroxene partly equilibrated with hydrous felsic melt. However, identical microstructures may be produced by ordinary reaction relationships between magmatic pyroxene and melt, producing hornblende (e.g., Cawthorn & O'Hara, 1976). Furthermore, as noted by Vernon & Flood (1982) and detailed by Flood *et al.* (in prep.), clinopyroxene grains partly replaced by amphibole in at least one granitoid pluton show oscillatory zoning and so result from magmatic crystallization.

Flood *et al.* (1977) interpreted pyroxene-plagioclase aggregates in a rhyodacite as being either restite equilibrated with the melt at temperatures and pressures higher than those at which the normal phenocrysts crystallized, or as cumulate material. Therefore, some mafic aggregates in chemically related granitoids (Flood *et al.*, 1980) may have a similar origin.

A reasonable conclusion is that though some mafic aggregates in metaluminous granitoids could be of restite origin, unambiguous microstructural evidence is generally absent. Furthermore, even where mafic aggregates of doubtful origin exist, euhedral mafic grains typically are present also, suggesting that at least some of them crystallized from the melt. Even if overgrowth on restite xenocrysts is postulated, precipitation from the melt must still be involved. Therefore, the extreme view that all mafic grains in granitoids are modified restite is untenable.

Similar reasoning applies to mafic clots in peraluminuous (S-type) granitoids, in which a reaction relationship between magmatic orthopyroxene and melt to produce biotite is predicted by the experiments of Green (1976) and Clemens & Wall (1981). Microstructural evidence of this reaction is rare in granitoids, although it is present in some microgranitoid enclaves in the Cowra Granodiorite (Vernon *et al.*, in prep.). Rectangular aggregates rich in biotite and quartz in peraluminous granitoids of the Bundarra Suite, New England Batholith, N.S.W., originally may have been magmatic orthopyroxene that reacted with K-feldspar and water components in the liquid to produce biotite and quartz, although no orthopyroxene relics have yet been found.

With regard to biotite grains and aggregates in a peraluminous granitoid, Phillips *et al.* (1981, pp.52-3, fig.3a) have stated that "features expected in restite micas (sillimanite inclusions and coarse, foliated aggregates) are entirely lacking in the Strathbogie biotites". This typical absence of foliated aggregates also could be used to argue aginst a restite origin for biotite aggregates in metaluminous granitoids.

Restite (i.e., metamorphic) cordierite in peraluminous granitoids may be expected to show inclusions of sillimanite (White & Chappell, 1977, p.18) and/or spinel (Phillips *et al.*, 1981, p.59), as well as being anhedral and rich in inclusions (Phillips *et al.*, 1981, p.53). Some cordierite of this type in the Strathbogie Batholith, Victoria, may be restite, but most of the cordierite is euhedral, and its grainsize correlates with that of the enclosing rock, suggesting a magmatic origin (Phillips *et al.*, 1981, p.53). Similarly, almandine-rich garnet with many inclusions, especially sillimanite inclusions, may well be restite,

particularly if associated with rutile, which association indicates confining pressures of >700-800 MPa (7-8 kbar) according to Clemens & Wall (1981, p.118). However, euhedral, inclusion-free garnet could well be magmatic, as could anhedral garnet devoid of evidence of reaction and intergrown with felsic groundmass minerals in porphyritic granitoids (Phillips *et al.*, 1981, p.53). A detailed study of the peraluminous Strathbogie Batholith has shown that the amounts of undoubted restite present are so small that restite unmixing is unlikely to account for any significant chemical variation (Phillips *et al.*, 1981, p.59).

Plagioclase Cores

Proponents of the restite hypothesis (e.g., Presnall & Bateman, 1973; White & Chappell, 1977; Chappell, 1978; Wyborn, 1983) have suggested that apparently corroded ("patchy zoned") cores of plagioclase grains are residuals of restite that have been overgrown by magmatic, oscillatory zoned, typically more sodic plagioclase. The following are arguments against this hypothesis.

1. Identical inclusion-rich cores with patchy zoning occur in basalts, in which plagioclase cannot have been a restite mineral, on the basis of experimental data. Therefore, these criteria cannot be used to support the restite hypothesis. Resorbed cores also occur in gabbros (e.g., Maaløe, 1976, fig.5), for which the same argument applies.

2. In some of the cores, the patchiness appears to be crystallographically controlled, in which case dendritic growth is at least as plausible as corrosion (Hibbard, 1981, fig.3A).

3. Some of the plagioclase cores that are apparently corroded are themselves zoned (e.g., Vance, 1965, figs.2,3,5,6,8,17; Wiebe, 1968, pp.694-5; Raase, 1969, fig.1; Akahane, 1977, fig.10; Hibbard, 1981, fig.3B). This favours magmatic crystallization for the original core, rather than the metamorphic origin implied by the restite hypothesis. In some examples, the zones follow around the embayments, favouring dendritic growth (Hibbard, 1981, fig.3B), whereas in others they appear to be truncated. However, even if corrosion did occur, the zoning of the corroded core remnants is still evidence for a magmatic, rather than a restite origin, for the original core.

4. Many of the cores have overall euhedral shapes, which also favour a magmatic origin (Vance, 1962, p.644), although this does not apply to all examples (e.g., Chappell, 1978, p.274).

5. Even unzoned cores are not necessarily indicative of restite, as suggested by Wyborn (1983), because initial growth at small degrees of undercooling conceivably may produce unzoned crystals, and a "large" core may represent a relatively small volume of a crystal.

6. The small, rounded inclusions of pyroxene, hornblende, opaque grains and apatite that occur in some of these plagioclase cores (e.g., Thomas & Smith, 1932, p.278) are unlikely to indicate restite. Small inclusions are not common in high-grade metamorphic (granulite to upper amphibolite facies) rocks, such as those that would be expected to occur in the melting zone (White & Chappell, 1977; Chappell, 1978), larger and fewer inclusions being more typical (Vernon, 1968). Moreover, small inclusions of this type can be incorporated at any stage in the growth of plagioclase crystals in volcanic rocks (Fig.1), and so are not restricted to the cores. In fact some may have grown in melt inclusions trapped by locally cellular growth of plagioclase.

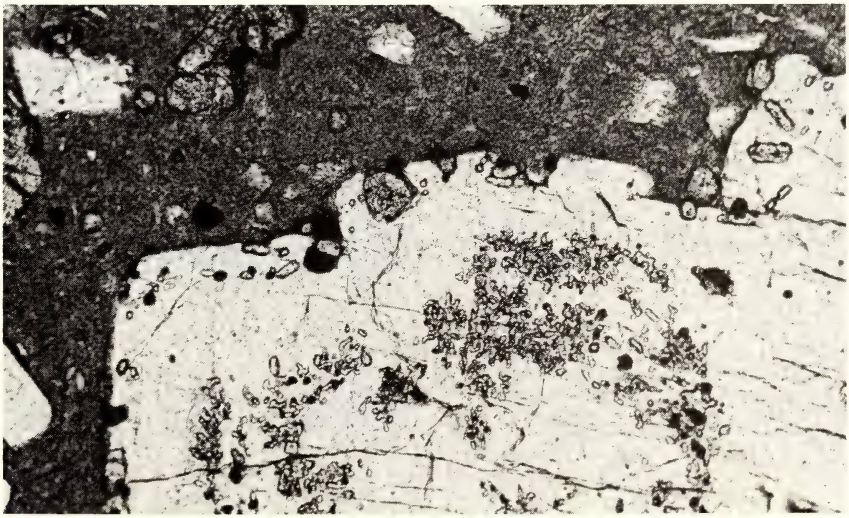

Fig. 1. Plagioclase phenocryst with inclusion-rich core ("mottled" in crossed polars) as well as small inclusions of pyroxene and an opaque mineral that have been either partly of completely incorporated during the last stages of growth of the phenocryst. Glassy andesite, Hunter Valley, N.S.W. Plane-polarized light; base 1.75 mm.

7. The compositions of the cores commonly are appropriate to near-liquidus crystallization, determined experimentally (Clemens *et al.*, 1983).

All these arguments weigh heavily against the use of mottled plagioclase cores, with or without inclusions, as indicators of restite.

Xenoliths

White & Chappell (1977, p.9) have suggested that much more than 99 percent of enclaves ("xenoliths") in granitoid plutons are of restite origin, the remainder being obvious wall-rock xenoliths.

Some peraluminous (S-type) plutons, such as the Cootralantra Granodiorite (White *et al.*, 1977), the Strathbogie Batholith (Phillips *et al.*, 1981) and the Cowra Granodiorite (Vernon & Flood, 1982) contain foliated metasedimentary xenoliths, such rocks being unrepresented in the exposed wall rocks. White & Chappell (1977) have inferred that they represent restite. Some contain assemblages indicative of high pressures appropriate to a likely source area, such as garnet-rutile (Clemens & Wall, 1981), but most either have been re-equilibrated to lower-pressure conditions (e.g., by the transformation of garnet + sillimanite to cordierite + spinel) or were extracted fortuitously from a lower-pressure metamorphic terrain above the source area.

White *et al.*, (1977, p.40) interpreted fragments of milky quartz in peraluminous granitoids as representing quartz veins in the source rocks. However, xenocrysts of milky and smoky quartz occur near xenoliths of pegmatite containing identical quartz in the Cooma Granodiorite, and identical quartz also occurs in pegmatites in migmatites adjacent to and intruded by the granodiorite. Therefore, pegmatitic quartz is an alternative to vein quartz as an explanation of at least some quartz xenocrysts in peraluminous granitoids (Vernon & Flood, 1982).

The so-called "mafic" xenoliths (microgranitoid enclaves; see later) are by far the most abundant type of enclave in metaluminous granitoids, and are generally the most abundant type in peraluminous granitoids as well. They have been interpreted as restite by Bateman *et al.* (1963), Presnall & Bateman (1973), White & Chappell (1977), Chappell (1978), Hine *et al.* (1978), and Griffin *et al.* (1978), and as modified restite by McBirney (1980). These enclaves are characterized by igneous microstructures (Flood & Vernon, 1979; Vernon & Flood, 1982), as will be discussed in more detail later. This effectively eliminates a restite origin for them, as restite aggregates should have either coarse-grained, granoblastic microstructures typical of high-grade metamorphic rocks (Kretz, 1966; Vernon, 1968) or foliated to mylonitic microstructures, if deformed. Alternatively, they may resemble coarse-grained cumulates, if the early-formed crystals separated from the melt (Flood *et al.*, 1977; Flood & Vernon, 1979). Some mafic xenoliths do show evidence of partial recrystallization (Flood, 1971; Chappell, 1978), but their original igneous microstructure is partly preserved (so that these are igneous hornfels xenoliths), and most of the "mafic" (microgranitoid) enclaves under discussion show no evidence of recrystallization.

In an attempt to explain the igneous microstructures while retaining a restite origin, it could be suggested that the enclaves represent restite plus interstitial melt that remained together during ascent of the magma (A.J.R. White, pers.comm.). In order for the enclave to hold together before crystallizing completely, the solid material must have constituted a continuous framework, which suggests the question: how could it have left the source area? In addition, if the interstitial melt crystallized to form the igneous grain shapes, why is the grainsize finer than that of the surrounding granitoid, especially since both the enclave melt and the granitoid melt should be minimum melts at the same temperature? Heterogeneous nucleation in the enclave is not a satisfactory explanation, because, according to the restite hypothesis, abundant solid restite should also be present in the host granitoid, providing ample opportunity for heterogeneous nucleation there as well. Also, where is the evidence of the relic, coarse-grained material that would be expected to occur between the igneous-looking material in the enclaves?

Despite an assertion to the contrary by White & Chappell (1977, p.17), the acicular apatite that is so characteristic of microgranitoid enclaves (Fig.2) is not indicative of restite, as metamorphic apatite is typically more equant, and may show curved boundaries formed by adjustment of grain boundaries in the solid state (Vernon, 1968, p.17). In fact, acicular and skeletal apatite crystals indicate magma quenching (Wyllie *et al.*, 1962), as discussed later. The same probably applies to elongate zircon crystals observed in some microgranitoid enclaves (Williams *et al.*, 1983).

Fig. 2. Needles of apatite in K-feldspar and biotite, in a microgranitoid enclave from the Moonbi Adamellite, southern New England, N.S.W. Plane-polarized light; base 1.75 mm.

STATUS OF THE RESTITE HYPOTHESIS

The foregoing discussion indicates that microstructural evidence of restite in high-level, metaluminous granitoids is meagre to absent, and that even in peraluminous granitoids it is limited. This suggests that alternative explanations of the linear chemical variation in many granitoid suites, such as magma mixing, should be considered, although the chemical details of this problem are outside the scope of this lecture.

The question that next needs attention is: if the microgranitoid enclaves are not of restite origin, what is their origin? The remainder of the paper will discuss this problem.

MICROGRANITOID ENCLAVES

Terminology

The rounded, dark "xenolithic" bodies that occur commonly in granitoid plutons are difficult to name accurately. As recognized by Phillips (1880), they are not xenoliths in the sense of being foreign fragments of solid rock (Walker & Skelhorn, 1966), for reasons discussed later. The French term "enclave" (e.g., Didier, 1973) covers all kinds of "xenolithic" bodies, and the term "inclusion" (Grout, 1937) is probably best reserved for inclusions of mineral grains in other mineral grains (Harker, 1909). The term "cognate xenolith" is a contradiction, as pointed out by Grout (1937), although most petrologists know what it means. Pabst's (1928) use of the term "autolith" is a sensible recognition of the close relationship to the enclosing granitoid. Although in one sense it implies material generated entirely from the granitoid itself, which is not necessarily entirely correct (see later), it could also reasonably be inferred to mean generation entirely within the granitoid magma. The second meaning is compatible with most hypotheses for the origin of these bodies considered to be feasible in this review, as discussed later.

The term "microgranular enclave" (Didier, 1973) is distinctive, but unintentionally gives the impression of a metamorphic microstructure, which is why Vernon & Flood (1982) used "microgranitoid" instead, the intention being to emphasize the essential granitoid microstructure and composition, recognized long ago by Phillips (1880). However, the term "microgranitoid xenolith" (Vernon & Flood, 1982) is not ideal, for reasons mentioned above, and the best compromise appears to be "microgranitoid autolith" or "microgranitoid enclave". Nonetheless, use of "microgranitoid xenolith" should cause few problems.

Literature

An examination of most of the prominent literature on microgranitoid enclaves (autoliths) has pointed to two papers of "benchmark" significance. Phillips (1880) was avowedly the first to use microscopic and chemical techniques to study xenoliths, and his paper has remained unbettered, in my opinion, except for that of Pabst (1928). Both papers are outstanding examples of careful observation and sensible interpretation. In addition, the book of Didier (1973) is a mine of information and ideas, especially in its assessment of the literature in French, and the recent paper of Hibbard (1981) is a stimulating account of magmatic mixing processes that may be responsible for the production of the enclave material, as discussed later.

Phillips (1880) clearly distinguished the rounded (ovoid) microgranitoid enclaves (which he called "concretions", "nodules", "patches" or "inclusions") from angular, metasedimentary xenoliths, which he noted are generally not appreciably altered by the granitoid, but may be penetrated and split apart by the magma (p.20). He called the rounded enclaves "fine-grained granitic patches or nodules" (p.1) and "fine-grained granite" (pp.13, 21), thus recognizing their essential granitoid character, which is embodied in the term "microgranitoid" (Vernon & Flood, 1982). He observed that (a) the enclaves are darker and finer-grained than the host granitoid (pp.1, 14, 19); (b) the enclaves consist of the same minerals as the granitoid, but plagioclase, biotite and hornblende typically are more abundant (pp.10, 14, 19); (c) the plagioclase in the enclaves may be zoned (p.10); (d) the boundary between enclave and granitoid is usually sharp (pp.1, 13), but may be gradational (p.1); (e) needles of apatite may be present in the enclaves (pp.18, 19); (f) a few enclaves enclose darker or lighter "patches", presumably representing double enclaves (p.2); (g) some enclaves contain K-feldspar megacrysts that are generally rounded, these being pink or white to match the colour of megacrysts in the enclosing granitoid (pp.2, 9, 19); and (h) enclaves occur at any distance from contacts (p.22). He inferred that the enclaves were "concretionary" in origin, and that they were "usually contemporaneous with the solidification of the general rock-mass" (p.20). Judging from the published discussion following his paper, it appears that many contemporary geologists agreed with him, especially with regard to his distinction between microgranitoid enclaves and xenoliths.

Pabst (1928) made similar observations to those of Phillips (1880) in an excellent descriptive survey of enclaves in the Sierra Nevada granitoids. He particularly emphasized evidence of distortion of microgranitoid enclaves (autoliths) caused by flow in the granitoid magma, his descriptions being similar to those presented in another excellent, but less comprehensive, descriptive paper by Gilbert (1906). Pabst also surveyed the available literature in German. Following Grubenmann and Riegner, Pabst decided that though the enclaves appear related in origin to the host granitoids, not the wall rocks, no clear origin of the enclaves could be suggested on the basis of evidence available to him. So he wisely contented himself with a listing of features that must be explained by a satisfactory hypothesis. However, he emphasized that the enclaves were not fully crystallized when distorted by flow of the granitoid. The implication is that they are magmatic in origin.

CHARACTERISTICS OF MICROGRANITOID ENCLAVES

The careful descriptions of Phillips (1880) and Pabst (1928), in particular, have given later workers a firm basis for making sound interpretations. To them we may add more recent observations, to give the

following list of features typical of microgranitoid enclaves.

Occurrence

1. Although most published descriptions are of microgranitoid enclaves in metaluminous (I-type) granitoids, they also occur in peraluminous (S-type) plutons (e.g., Brammall & Harwood, 1932; White *et al.*, 1977, p.40; Wiebe, 1968; Speer, 1981, pp.38-9; Phillips *et al.*, 1981, p.55; Vernon & Flood, 1982).

2. Their abundance appears unrelated to the number of hornfels xenoliths present (Pabst, 1928, p.335).

3. They are much more abundant than hornfels xenoliths in both I-type (Chappell, 1978) and S-type (Phillips *et al.*, 1981, p.55; Vernon *et al.*, in prep.) plutons.

4. In S-type plutons, they are generally more abundant than metasedimentary xenoliths of all kinds (Phillips *et al.*, 1981, p.55; Vernon & Flood, 1982).

5. Their abundance generally is not related to the contact of the pluton (e.g., Phillips, 1880, p.22; Pabst, 1928, p.335).

6. Their distribution commonly is irregular, but may be uniform over relatively large areas, and they may be concentrated in swarms apparently related to flow in the granitoid magma (e.g., Pabst, 1928).

7. They are generally unrepresented among the country rocks at the level of exposure (Grout, 1937; Didier, 1973). Pabst (1928, pp.356, 358, plate 54) emphasized that microscopic features may be useful in distinguishing true microgranitoid enclaves from superficially similar igneous xenoliths incorporated from wall-rocks.

8. They occur in host rocks from gabbroic to granitic in composition, but are rare in the most leucocratic rocks. They are probably most abundant in granodiorites and adamellites or quartz diorites and quartz monzonites (Pabst, 1928, p.337).

9. Some are enclosed in other microgranitoid enclaves, and some enclose metasedimentary xenoliths, both being known as "double enclaves" (Didier, 1973).

10. They appear to be restricted to relatively high-level plutons (Fershtater & Borodina, 1977, p.458).

Shape and Size

11. They generally have rounded to ovoid shapes (Figs.3, 4, 5; Phillips, 1880; Pabst, 1928, p.332), though subangular and, more rarely, angular examples may be present (e.g., Pabst, 1928, p.332). Some have serrated or cuspate margins, with lobes convex towards the host granitoid (e.g., Grout, 1937, plate 10, fig.2). Elongate enclaves are markedly ellipsoidal to lenticular, as shown in Fig.6 (e.g., Pabst, 1928, fig.2, plate 46b).

12. They are generally rather small but variable in size, a commonly reported size range being about 1cm to 1m in diameter (e.g., Pabst, 1928).

13. They typically have sharp contacts with the granitoid (Figs.3-6), although diffuse contacts have been reported (e.g., Pabst, 1928, p.339; Didier, 1973), and on the microscopic scale, grains of quartz and K-feldspar from the granitoid may extend slightly into the enclave, to poikilitically enclose plagioclase and mafic grains (e.g., Pabst, 1928, p.343).

14. Generally the granitoid adjacent to the enclave is not obviously modified (Figs.3-6), as noted by Thomas & Smith (1932, p.291).

15. They commonly are aligned in any primary flow foliation in the granitoid (Fig.6; Pabst, 1928, fig.2), and discoidal inclusions generally are parallel to the nearest contact (Bateman *et al.*, 1963, p.D17), their alignment following changes in direction of the contact (e.g., Pabst, 1928, p.333).

16. They commonly are progressively flatter as the contact of the pluton is approached (Pabst, 1928; Bateman *et al.*, 1963, p.D17; Chapman, 1969; Pitcher & Berger, 1972).

17. Their degree of elongation correlates with the intensity of flow foliation (Fig.6) in the host granitoid, suggesting that both enclaves and granitoid were deformed similarly during the flow.

Fig. 3. Rounded microgranitoid enclave with uniform, even-grained microstructure in the Cowra Granodiorite, N.S.W.

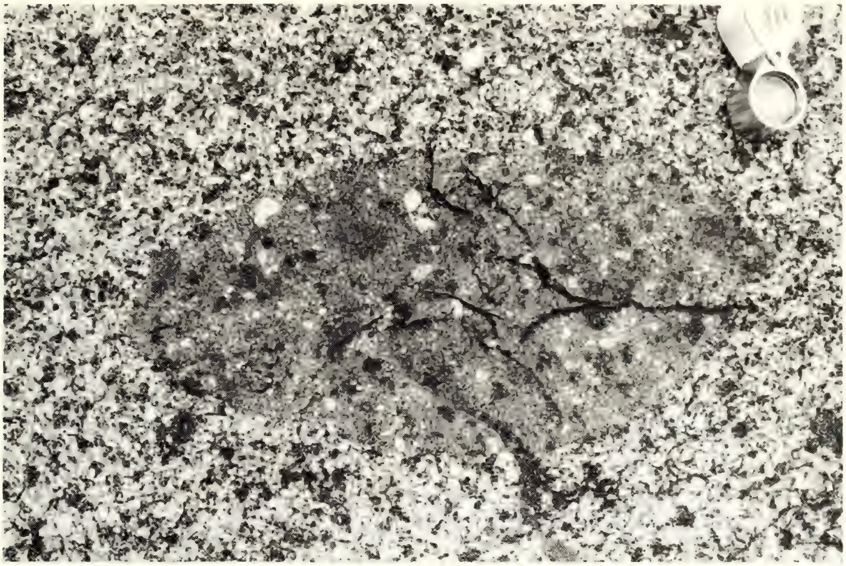

Fig. 4. Rounded microgranitoid enclave, with plagioclase and mafic phenocrysts, in the Cowra Granodiorite, N.S.W.

Fig. 5. Intimate veining of gabbroic diorite (dark) by tonalite (light) at Tuross Head, N.S.W. The tonalite contains rounded enclaves of the gabbroic diorite, and some diorite globules are still attached to the main body (centre and left), suggesting that the enclaves had rounded shapes right from the start of their incorporation.

Fig. 6. Elongated, lenticular microgranitoid enclaves in the Tuross Head Tonalite, N.S.W. The enclaves are aligned parallel to a flow-foliation in the host granitoid.

18. They may be extremely elongated (Fig.6; Pabst, 1928, p.334) - up to 40:1 elongation in the Tuross Head Tonalite, N.S.W. - without showing microstructural evidence of grain deformation or recrystallization (e.g., Pabst, 1928, fig.3), as shown in Fig.7. Therefore, the extension appears to have been accomplished by relative movement of crystals and melt (Vernon *et al.*, 1983).

19. Mineral grains in elongated enclaves have a similar preferred orientation to those in the adjacent foliated granitoid rock (Fig.7), but the preferred orientation may be stronger in the enclaves (Pabst, 1928, p.353; Hurlbut, 1935, p.625).

20. Elongated enclaves may be deflected, along with the flow foliation in the granitoid, around large metasedimentary xenoliths (Hurlbut, 1935, p.616). The flow foliation in the granitoid is deflected around the enclaves and does not pass through them (e.g., Sen, 1956, p.649-650).

21. Closely associated enclaves may interfere with and indent each other, but are always separated by at least a thin fillet of granitic rock (Gilbert, 1906, p.324), as seen at Tuross Head. They must have "yielded to squeezing with the same facility as the magma. Had they been more rigid than their matrix, they would have been forced into contact before suffering elongation" (Gilbert, 1906, p.325-6). Thus, although the enclaves must have been more viscous than the granitoid, because of their shapes, the rheological properties of both were similar.

22. Some enclave swarms apparently have been localized by projections of country rock into the magma (Pabst, 1928, p.337).

23. Some enclaves have smooth, pillow-like shapes on their upper chilled margins and load-cast types of indentations on their lower unchilled margins, these relationships being consistent in a particular area of the pluton (Didier, 1973, p.110, fig.46). This has been interpreted as lighter granitic magma penetrating mafic pillows as it tries to rise (Didier, 1973, p.110).

Microstructure

24. Their microstructures generally are uniform throughout each enclave (Fig.8), though some enclaves have finer-grained margins (Fig.9); the grainsize averages about 0.3mm; Pabst (1928, p.342) reported a groundmass grainsize range of 0.1-1mm; the mafic minerals are generally finer-grained than the felsic minerals, as in the host granitoid (e.g., Pabst, 1928, p.343).

25. The orientation of grains is generally random (Fig.8) though flow alignment, especially of plagioclase laths (Fig.10) is common (e.g., Pabst, 1928, p.343); the alignment may be parallel to the margins of the enclave, and may be deflected around phenocrysts in the enclave (Taylor *et al.*, 1980).

26. They have microstructures typical of fine to medium-grained igneous rocks (Figs.8, 9, 10, 11, 12), as discussed later (e.g., Phillips, 1880; Wells & Woolridge, 1931; Brammall & Harwood, 1932; Thomas & Smith, 1932).

27. They typically contain apatite needles (Fig.2; Phillips, 1880, pp.18, 19; Pabst, 1928, p.349; White & Chappell, 1977), and elongate zircon crystals have also been reported (Williams *et al.*, 1983, p.84).

28. Their plagioclase grains may have "corroded" (patchy-zoned) cores, with or without small rounded mafic inclusions (e.g., Pabst, 1928), and more sodic rims, with or without oscillatory zoning.

29. Some of them contain megacrysts of K-feldspar, which may be mantled with oligoclase (e.g., Phillips, 1880; Thomas & Smith, 1932; Hibbard, 1981).

30. They may contain rounded quartz grains ("ocelli", ?xenocrysts) rimmed by fine-grained

Fig. 7. Microstructure of part of an elongated microdiorite enclave in the Tuross Head Tonalite, showing strong alignment of plagioclase laths, but no evidence of internal crystal deformation or recrystallization. The enclave is similar to the more elongated enclaves of Fig.6. Crossed polars; base 4.4 mm.

Fig. 8. Microstructure of microgranitoid enclave, showing abundant, elongate laths of twinned, zoned plagioclase, many of which are sub-poikilitically intergrown with biotite and quartz. Many plagioclase laths are random, but locally they are poorly aligned in a rough flow foliation. New England Batholith, N.S.W. Crossed polars; base 4.4 mm.

Fig. 9. Chilled margin to microgranitoid enclave (above and right) against granitoid host (bottom-left). Marulan Granodiorite, N.S.W. Crossed polars; base 4.4 mm.

Fig. 10. Local flow alignment of plagioclase laths, adjacent to area of quartz poikilitically enclosing plagioclase and biotite, in a microgranitoid enclave from the Bathurst Batholith, N.S.W. Crossed polars; base 4.4 mm.

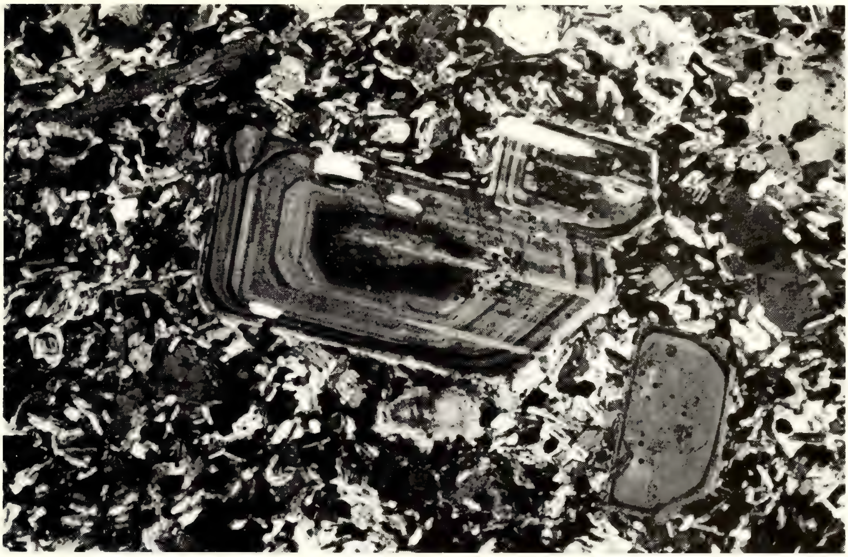

Fig. 11. Microgranitoid enclave, consisting of euhedral, oscillatory zoned phenocrysts of plagioclase, set in a groundmass consisting mainly of random plagioclase laths, biotite and interstitial quartz. Marulan Batholith, N.S.W. Crossed polars; base 4.4 mm.

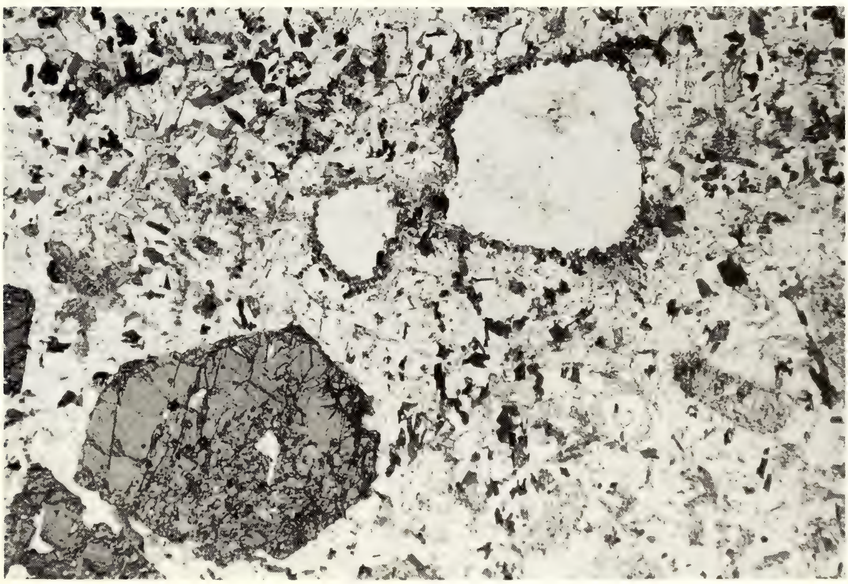

Fig. 12. Large rounded grains (?xenocrysts) of quartz rimmed by fine-grained mafic (orthopyroxene-rich) aggregates in a microtonalite enclave with phenocrysts of orthopyroxene (bottom-left) and altered plagioclase (right). Cowra Granodiorite, N.S.W. Plane-polarized light; base 4.4 mm.

mafic minerals, as shown in Fig.12 (e.g., Pabst, 1928, p.348; Wells & Woolridge, 1931, p.204; Thomas & Smith, 1932; Vernon *et al.*, in prep.).

31. They may or may not show evidence of replacement of pyroxene by hornblende, hornblende by biotite, and orthopyroxene by biotite (e.g., Thomas & Smith, 1932, p.283).

32. They have compositionally and microstructurally similar counterparts of similar size in calcalkaline volcanic rocks (e.g., Wilkinson *et al.*, 1964, pp.469-70); some of these contain interstitial volcanic glass and skeletal, zoned crystals of hornblende and plagioclase, indicating a magmatic condition (Eichelberger, 1978; 1980, fig.1). Some show chilled rims, and acicular apatite is common.

Composition

33. They are darker and finer-grained than their host granitoids (Figs.3-6; e.g., Phillips, 1880; Pabst, 1928).

34. Though they are consistently more mafic than their host granitoids, they generally are not strictly mafic (although they are often referred to as such), but are intermediate to silicic in composition (e.g., Didier, 1973).

35. Chemically they fall on or near variation trends for their host granitoids, with a wide range in SiO_2 percentages; e.g., 53-74 for microgranitoid enclaves in the Dartmoor granitoids (Brammall & Harwood, 1932, fig.5); 52-65 for the Moruya suite, N.S.W. (unpubl. data), and 52-65 for the Cowra Granodiorite, N.S.W. (Vernon *et al.*, in prep.).

36. They have the mineral assemblages and abundances of quartz diorites, quartz monzonites, quartz syenites, tonalites, granodiorites and adamellites (e.g., Didier, 1973, fig.97).

37. Hornblende and biotite are the typical mafic minerals in microgranitoid enclaves in metaluminous (I-type) plutons, whereas biotite ± orthopyroxene ± cordierite are the typical mafic minerals in microgranitoid enclaves in peraluminous (S-type) plutons (e.g., Vernon *et al.*, in prep.; Fig.12).

38. Their mineral assemblages are generally the same as those in the surrounding granitoid, but the proportions may be different (e.g., Phillips, 1880; Pabst, 1928, p.343) and the compositions are generally slightly but consistently different (e.g., Vernon *et al.*, in prep.), especially for plagioclase, which is commonly more calcic in the enclaves (Pabst, 1928, table 3). Particular mineralogical features of a granitoid, such as sphene or phenocrysts of hornblende, may be reflected in the enclaves (Pabst, 1928, p.358).

39. The enclaves have a relatively large range in composition in a single pluton (e.g., Pabst, 1928).

40. Microgranitoid enclaves in the Cowra Granodiorite, N.S.W. contain magmatic plagioclase, orthopyroxene and cordierite, indicating crystallization at less than 200 MPa (2 kbar), according to the experimental data of Clemens & Wall (1981). Therefore, at least some microgranitoid enclaves crystallize at granitoid emplacement levels.

IGNEOUS MICROSTRUCTURE

In my opinion, the most important feature of microgranitoid enclaves is their igneous microstructure. This was clearly recognized by Phillips (1880), Harker & Marr (1891), Harker (1909) and Pabst (1928). The common presence in the enclaves of (a) euhedral phenocrysts of plagioclase with oscillatory zoning (Figs.11, 12), hornblende, quartz, and orthopyroxene (in peraluminous varieties (Fig.12)), (b) abundant zoned plagioclase laths (Figs.7-12; Pabst, 1928, p.345), (c) poikilitic quartz (Figs.8, 10), K-feldspar or biotite (Fig.8), and (d) flow alignment of plagioclase laths (Fig.7) or phenocrysts (Pabst, 1928, p.342), favours an igneous, rather than a metamorphic microstructure. Hornfels xenoliths (including those of igneous parentage) can readily be distinguished from the microgranitoid enclaves on the basis of their metamorphic microstructures, as emphasized by Grout (1937). Moreover, minor intrusions of undoubtedly igneous origin (e.g., Joplin, 1964, figs.49c, 52c) can be matched microstructurally with the microgranitoid enclaves, as pointed out for lamprophyre dykes near the Shap Granite by Harker (1909).

The acicular apatite that is so characteristic of the microgranitoid enclaves (Fig.2; Phillips, 1880, pp.18, 19; White & Chappell, 1977) indicates a magmatic quench origin, according to the experiments of Wyllie *et al.* (1962), which are supported by the common occurrence of acicular apatite in the mesostasis of rapidly cooled volcanic and subvolcanic rocks.

Williams *et al.* (1983, p.84) described euhedral, very elongate (commonly greater than 10:1 in aspect ratio) crystals of zircon in some microgranitoid enclaves in a metaluminous granitoid pluton. The zircon crystals resemble those in some volcanic rocks and tuffs, suggesting a quench origin. Williams *et al.* (1983) suggested that the zircon crystallized from partly molten enclaves late in the history of the enclosing magma, but presumably this would imply slow cooling, which is inconsistent with the shape and volcanic similarities of the zircon crystals. Intuitively, zircon, being among the most refractory minerals, would be expected to be one of the most likely members of a restite assemblage. Yet here it is magmatic, indicating that a restite origin for the enclaves is most unlikely.

The fine grainsize in an otherwise plutonic environment suggests that the microgranitoid enclaves represent quenched magmatic rocks. The question is: how did the quenching occur? Several possible mechanisms are discussed below, after a consideration of the role of contamination in the formation of the enclaves.

THE ROLE OF CONTAMINATION

For most of this century, thoughts on enclaves and hybridism have been dominated by the concept that they develop by "reciprocal reaction" between granitic magma and solid rock, following the theoretical analysis of Bowen (1922), as developed by Nockolds (1933). The basic idea is that solid rock fragments are converted to igneous-looking rocks and the granitic magma is enriched in mafic components by chemical exchange with, and physical breakup of, enclaves. A detailed summary has been given by Didier (1973).

The reasoning seems to have been that because enclaves were assumed to be fragments of various types of solid country rocks, they must have undergone extensive changes while in the magma, in order to explain the observed mineralogical similarities to the host granitoid. Grout (1937) put the viewpoint most strongly by stating that because most country rocks are sediments, and shale is the most common sedimentary rock, it follows that most microgranitoid enclaves, of necessity, are transformed shales. Ironically, four years later he found it difficult to accept the idea that igneous-looking granitoid rocks could be formed by granitization (Grout, 1941).

The main problem with these interpretations involving contamination is that the microgranitoid enclaves have igneous microstructures, whereas metamorphic microstructures should be the result of recrystallization and neocrystallization in the solid state, even if metasomatism was involved. Nockolds (1933) invoked intimate penetration and crystallization of felsic melt in the enclaves, in order to explain the interstitial, commonly poikilitic quartz and K-feldspar. However, I know of no clear microstructural evidence for this process.

Grout (1937, p.1553) tried to minimize the problem by suggesting that igneous microstructures are not easy to recognize. However, he emphasized strongly that metamorphic microstructures are distinctive, and these are lacking in the microgranitoid enclaves, although they are present in the few accompanying hornfels xenoliths (including hornfelses of igneous origin), as clearly pointed out by Pabst (1928, pp.356, 358, plate 54).

Another problem with the contamination hypothesis is that the enclaves are consistently finer-grained than the host granitoid. Why should this necessarily be so if they underwent high-temperature alteration in the solid state, apparently in the absence of deformation?

The main question that must be asked is whether much reaction between xenoliths and magma ever occurs, at least as far as the microgranitoid enclaves in high-level plutons are concerned. Microgranitoid enclaves generally show no clear evidence of such reaction (e.g., Pabst, 1928, p.351). Those in the Cowra Granodiorite commonly have orthopyroxene, whereas this mineral is absent from the host granodiorite, biotite having been stable instead (Vernon *et al.*, in prep.). In some enclaves, orthopyroxene apparently has been partly replaced by biotite, but the degree of replacement is unrelated to the edges of the enclaves, and so it may well have been a magmatic reaction of the type to be expected in peraluminous granitoid magmas (e.g., Green, 1976; Clemens & Wall, 1981). A similar interpretation may apply to the partial replacement of pyroxene by hornblende in metaluminous microgranitoid xenoliths (e.g., Thomas & Smith, 1932, p.283).

Although examples of physical breakup of enclaves by penetration of discrete tongues of granitoid magma have been described (e.g., Phillips, 1880, p.20; Pabst, 1928, p.342; Nockolds, 1933; Didier, 1973), it appears that, once formed, the microgranitoid enclaves were sufficiently stable in the magma to avoid pervasive chemical and microstructural modification, as recognized by Larsen (1948, p.162). Similarly, most metasedimentary schistose and hornfelsic xenoliths generally show little evidence of reaction with the magma and little or no tendency towards rounding-even xenoliths of high-grade metamorphic origin. This shows that enclaves that have spent most time in the granitoid magma need not be much altered. It could be argued that the microgranitoid enclaves were in the magma for only a relatively short time, but in view of the similarity between the minerals of the enclave and the host granitoid, they must have had the same cooling period. Therefore, the resistance of the enclaves to recrystallization and increase in grain-size must be due to stable minerals and grain-boundary configurations, as well as to an absence of strain.

The foregoing discussion is not meant to deny the possibility of some recrystallization and neocrystallization in true xenoliths and of chemical interaction between certain reactive rock-types and granitic magma (e.g., Pabst, 1928, p.355; Grantham, 1928, pp.318-9; Osborne, 1931), especially calcareous and ultramafic xenoliths (Didier, 1973). However, the evidence indicates that many types of enclave, and microgranitoid enclaves in particular, do not show evidence of much or any solid-state reaction with the host magma. The "zoned enclaves" inferred by de Albuquerque (1973, p.491) to be restite xenoliths modified (i.e., granitized) round their edges by the enclosing magma, in fact appear to be double enclaves composed of a metasedimentary xenolith surrounded by a peraluminous microgranitoid enclave with an igneous, not a metamorphic, microstructure (de Albuquerque, 1973, p.483, plates III, IV). Double enclaves consisting of hornfels xenoliths inside microgranitoid enclaves are relatively common (e.g., Didier, 1973), and, because the two are separated by a sharp contact, they do not support the idea that microgranitoid enclaves result from the action of granitoid magma on hornfels xenoliths. A preferable explanation is that dislodged hornfels fragments are accidentally incorporated in the microgranitoid material, whatever its cause (Thomas & Smith, 1932, p.290; Pitcher & Berger, 1972, p.139; Vernon & Flood, 1982).

In a review of assimilation, McBirney (1979) gave many detailed examples of assimilation of igneous and sedimentary rocks in mafic magmas. However, equivalent examples for granitic magmas were not given, apart from xenocrysts, which could equally well be explained by magma mixing (see later), and the Brittany enclaves of Thomas & Smith (1932), which, as McBirney (1979, p.323) noted, may have been partly molten when mixed with the granitoid. This absence of clear examples also suggests that

contamination of granitoids by solid rock may have been greatly overestimated.

MICROGRANITOID ENCLAVES AS MAGMA GLOBULES

The fine-grained, igneous microstructures of the microgranitoid enclaves, together with their commonly rounded shapes and the evidence of magmatic flow of many of them, suggest that the material that gave rise to the enclaves was magma that crystallized rapidly. Walker & Skelhorn (1966, pp.99-100), Eichelberger (1978, 1980) and Hibbard (1981) have suggested that the enclaves may be the result of the mingling of mafic magma globules with a granitoid magma. Their interpretation is confirmed by my analysis of more comprehensive evidence, apart from their suggestion that the globules are mafic, because most enclaves are intermediate or silicic, as noted previously. However, as pointed out by McBirney (1980), evidence for the coexistence of magmas does not indicate by itself how the magmas were formed. Therefore, any process capable of supplying magma globules of the right compositional range could contribute to the enclave magmas.

For example, numerous local, fine-grained margins and apophyses to plutons have been described (e.g., Bateman *et al.*, 1963, p.D15; Didier, 1973) and this material is a possible source. So are small intrusions chilled against cool country rock (e.g., Goodspeed, 1948, p.519; Grout, 1937, p.1564; Wiebe, 1968, p.702; Flood & Vernon, 1979; Vernon & Flood, 1982). However, if these intrusions are the main source of the enclaves, why aren't hornfels xenoliths just as common (Flood & Vernon, 1979; Vernon & Flood, 1982)?

Alternatively, the enclaves may represent parts of the main pluton itself that crystallized rapidly against the upper walls and roof, and around detached fragments of the upper parts of the magma chamber, while becoming differentiated from the host granitoid magma (Phillips *et al.*, 1981; Vernon & Flood, 1982). Conceivably, this could involve thermal quenching or pressure quenching; the pressure quenching model has been outlined by Vernon & Flood (1982) and is being elaborated by Flood (in prep.).

The large size of most granitoid plutons raises questions about the ability of thermal quenching to produce rocks of appropriate grainsize, especially in view of the absence of chilled margins around the main, lower parts of granitoid batholiths. Hibbard (1981, p.158) has questioned both forms of marginal quenching, stating that "... quenching in the plutonic environment requires a cooling mechanism independent of conductive heat transfer to wall rock and also independent of sudden loss of volatile phases that could only occur late in the crystallization of most magmas and therefore after much dendritic plagioclase had already been formed" (referring to rapid growth of plagioclase in granitoid and enclaves). Hibbard (1981) presented detailed evidence that magma mixing is involved in the formation of enclave magmas, as discussed later.

If fragments of solid, fully crystalline marginal or external quench material are inferred to be the main source of the enclave material, presumably they would require rounding by solution or other forms of attrition in the granitoid magma, in order to explain the commonly rounded shapes of the enclaves. However, hornfels xenoliths generally show little evidence of rounding (e.g., Phillips, 1880), and so the rounded shapes may well be primary features of the enclaves. Of course, the less common angular enclaves could be due to the incorporation of solid quench fragments. On the other hand, magma can break, like pitch, if rapidly deformed (Walker, 1969; Blake *et al.*, 1965), and so angular enclaves could have been magmatic when incorporated, as are some of the enclaves in clear examples of magma mingling described later.

Enclaves with flow structures (Figs.7, 10) and distorted enclaves with no evidence of crystal plasticity or recrystallization (Figs.6, 7) are best explained by inferring that they were magma globules when being deformed. An alternative might be to postulate flaking off of very flat pieces of solid quenched rock that happened to have a strong preferred orientation of the constituent minerals, but then the degree of elongation of these fragments would not be related to the intensity of flow of the magma, as is the situation (e.g., at Tuross Head, discussed later). Flaking off of flat fragments has been suggested by Chapman (1969) and Taylor (1976), but Taylor's photograph shows that the enclaves are ellipsoidal to lenticular, favouring flow of magma globules.

As mentioned previously, the microgranitoid enclaves are almost invariably more mafic than their host granitoid. Therefore, the magma globules inferred to be their forerunners would have been hotter than the granitoid magma. Consequently, mingling of the enclave globules in the cooler granitoid magma results in loss of heat, increase in viscosity, and increase in the degree of undercooling of the enclaves. The increased viscosity inhibits mixing of the magmas and produces dominantly rounded enclave shapes, and the increased undercooling causes a finer grainsize in the enclave than in the granitoid. Even a small increase in the degree of undercooling can be effective, as discussed later, so that even enclaves that are only slightly more mafic than the host granitoid can have finer grainsizes than the granitoid.

Distinction should be made between magma mingling or commingling (Harker, 1909), which involves interpenetration of two or more magmas without pervasive mixing of the melts, and magma mixing, which involves homogenization of melt phases and the conversion of any pre-existing crystals to minerals stable in the hybrid melt, or their armouring by stable minerals.

Complete miscibility in common calcalkaline melts is indicated by phase equilibrium experiments (e.g., Bowen, 1928) and mixing experiments (Yoder, 1973; Kouchi & Sunagawa, 1982, 1983). It is confirmed by experimental and natural evidence of chilling of mafic against felsic magma, since thermodynamically immiscible liquids should coexist without chilling (Taylor *et al.*, 1980, p.433). Therefore, any failure of two calcalkaline melts to mix completely in nature must be due to kinetic factors, related principally to viscosity differences.

Before discussing this process for the plutonic environment, it is worth examining examples of magma

mingling and mixing in the subvolcanic environment, which provide some of the clearest evidence of the process in an arrested state.

MAGMA MINGLING IN THE SUBVOLCANIC ENVIRONMENT

A clear example of magma mingling occurs in a granite porphyry ring dyke that cooled quickly enough to preserve incipient stages of the process, in New Hampshire (Reid *et al.*, 1980). Droplets of basalt occur in the felsic rock, the basalt being variolitic, with skeletal plagioclase, ilmenite and apatite. The grainsize decreases towards the margins of the droplets, indicating chilling. Lobes of basalt appear to have engulfed K-feldspar phenocrysts of the felsic rock.

Many other examples of the mingling of mafic and felsic magmas in composite intrusions in the subvolcanic or highest-level plutonic environments have been described, as reviewed by King (1964), Blake *et al.* (1965), and Walker & Skelhorn (1966). Some of the earliest descriptions were those of Harker (1904; 1909, pp.343-346), who discussed examples of intimate mingling of basalt and granophyre in Tertiary composite intrusions of the western isles of Scotland. He inferred that in some examples the basalt was "not wholly crystallized" and that "basic and acid magmas were intruded almost simultaneously" (Harker, 1909, p.344).

The main features shown by these occurrences are: (a) the mafic magma is chilled against the felsic magma; (b) the felsic magma commonly intricately veins the mafic rock, and there may be flow structure in the felsic vein and chilling in the mafic margin to the vein; (c) the felsic magma stays molten longer than the mafic magma, and is highly mobile, so that it may vein fractured, solid mafic rock, in which case the mafic rock does not show chilling against the felsic veins; (d) mafic enclaves occur in the felsic rock, the enclaves being rounded (pillow-like) to wispy, commonly with crenulate margins; (e) the mafic enclaves generally are finer-grained than the main body of mafic rock, and some have chilled edges; and (f) the local occurrence of double enclaves and of enclaves somewhat unlike the adjacent mafic rock suggests that some enclaves were brought in from elsewhere (King, 1964, p.286).

The fluidity of the felsic melt - evidenced by the intimacy of the net-veining and the flow structure in some felsic veins (Blake *et al.*, 1965) - may be enhanced by a separate gas phase, since druses with hydrous minerals occur in some granophyres, and since some mafic pillows show a change from pyroxene in their interiors to hornblende and even biotite at their margins, suggesting transfer of water from the felsic magma. However, most of the mobility is probably due to transfer of heat from the mafic magma, as indicated by the chilling.

The higher viscosity of the mafic magma relative to the felsic magma is evidenced by the general absence of mafic veins in felsic rock, the absence of felsic enclaves in mafic rock, and the pillow-like shapes of the mafic enclaves. Locally a mafic dyke cuts felsic rock, which can occur if the felsic material becomes so viscous that it fractures, like pitch, under the action of a rapidly applied stress (Blake *et al.*, 1965, p.40).

McSween *et al.* (1979) interpreted composite lamprophyre-granophyre dykes in South Carolina as the result of magma mingling (producing pillow-like structures and net-veining) and local magma mixing (producing small amounts of hybrid biotite granophyre melt). Across contacts that are gradational on the thin-section scale, the biotite composition remains constant, but the plagioclase is more calcic towards the lamprophyre.

MAGMA MINGLING IN THE PLUTONIC ENVIRONMENT

Harker (1909, pp.340-3) discussed examples of hybridism in plutonic complexes of the British Tertiary suite, in which mafic and felsic rocks are in close association, enclaves of mafic rock occurring in the felsic rock. He described intimate veining of mafic by felsic rock and evidence of acidification of the more mafic rock and basification of the more felsic rock. In places, the heterogeneous mass of mingled mafic and felsic rock has been drawn out by contemporaneous flow to produce a "gneissic banding", as in the Tertiary "gneisses" of Rum. Harker envisaged softening of formerly solid gabbro by "metamorphism, by fusion and recrystallization, and by partial impregnation". Following Bowen (1922, 1928), we now know that melting of solid gabbro by felsic magma is very unlikely, and so the mafic fraction in the layered complex was probably magma from the start of the mingling process. Harker obviously appreciated the need for coexisting magmas to explain the layered structure. These "gneisses" may be the plutonic equivalents of layered, mingled mafic/intermediate-felsic volcanic rocks and of the interlayered mafic and felsic melts produced experimentally by Kouchi & Sunagawa (1982, 1983).

A clear example of magma mingling in the plutonic environment was described by Wells & Woolridge (1931) on the island of Jersey, where at the well exposed upper contact, a granitoid pluton has intricately penetrated and dislodged enclaves from a roof of gabbro. They noted that the enclaves are commonly rounded, with serrated outlines, some showing transitions into a schlieren-like interfingering with the granitoid (Wells & Woolridge, 1931, fig.16). They also observed that the enclaves are commonly finer-grained towards their margins, and stated that "the impression is conveyed that the xenoliths have been actually chilled against the invading magma, which is of course absurd" (Wells & Woolridge, 1931, p.190). Nowadays this interpretation is not absurd, but the idea was so repugnant to Wells & Woolridge that they clung firmly to Bowen (1922) and explained the enclaves and their variety by the incorporation of fragments of solid gabbro, followed by varying degrees of reaction with the felsic magma. However, their photomicrograph (fig.23, p.204) of a "hybrid rock" illustrates a microdioritic rock with an igneous microstructure, containing the usual apatite needles and also local, rounded, large quartz grains (up to about 30 mm across) with fine-grained amphibole rims. As discussed later, such rimmed quartz grains are commonly produced by magma mixing. In addition, their photomicrograph (fig.22) of the fine-grained margin of an enclave also looks microdioritic and "the mineral composition is of a quartz-mica diorite or tonalite" (Wells & Woolridge, 1931, p.204).

An "almost identical" situation in the Trégastel-Ploumanac'h Granite, Côtes du Nord, France, was described by Thomas & Smith (1932). Gabbroic diorite has been veined by granite, producing rounded, igneous-looking enclaves and a "mixed zone", in which the granitoid is enriched in plagioclase, biotite and hornblende, and depleted in K-feldspar. Pink K-feldspar megacrysts in the mixed zone are rounded with white rims (rapakivi structure), but are not rimmed elsewhere. All these features were attributed to chemical modification of the granitic magma by components from the more mafic material.

Identical rimmed megacrysts of feldspar occur in the more mafic rock, some transgressing the contact. Ovoid quartz "ocelli", up to 1 cm across, in diorite are fringed with hornblende, and may be former miarolitic cavities or, more likely, phenocrysts from the granite magma that were incorporated in the more mafic material. This interpretation is supported by the fact that quartz grains in the granite are up to 1 cm across.

Most of the enclaves are dioritic, monzonitic and tonalitic in composition and igneous in microstructure, and the largest (about 3 m across) may have relics of labradorite and clinopyroxene, evidently from the more mafic parent. Thomas & Smith (1932, p.289) noted that "typical igneous structures are preserved in the basic mass throughout all phases of hybridization". They explained this by "the mass being reduced to a semi-fluid or plastic condition by the presence of interstitial melt"; so they evidently saw the need for magma mingling, although they imagined that the mafic parent was initially solid, and they explained the enclaves as being due to the reaction between solid mafic rock and granitic magma, in the tradition of Bowen (1922). The idea of granitic magma melting solid mafic rock may have caused them an obvious problem, because they invoked a vague process, namely "general recrystallization" (p.289). As noted by Hibbard (1981), the coexistence of felsic and more mafic magma resolves the dilemma.

Wiebe (1973) described evidence of the intrusion of basalt and basaltic andesite magmas into a floored chamber of fractionating andesitic magma on Cape Breton Island, Nova Scotia. The magma injections crystallized as chilled pillows and lenses of hornblende gabbro in layered diorite. Evidently the chilling occurred too quickly to permit significant mixing of the two magmas. This occurrence shows that coexistence of mafic and intermediate magmas is also possible in the plutonic environment.

M.A. Etheridge, V.J. Wall and I have observed evidence of magma mingling at Tuross Head, N.S.W., the details of which will be published elsewhere. Preliminary notifications of this occurrence have been made by Blake (1981, p.97) and Vernon *et al.* (1983). Intrusions of gabbroic diorite and tonalite have been juxtaposed and show intricate contact relationships. Intimate veining of the gabbroic diorite by the tonalite (the veins being irregular and without matching walls) is typical (Fig.5) and the contact between the two is lobate to crenulate (Fig.5). Chilling of the more mafic against the more felsic rock is apparent in places, and has been confirmed by examination of thin sections. Rounded, blob-like extensions of the gabbroic diorite locally project into the tonalite, and enclaves can be seen in all stages of incorporation. Their shapes are rounded from the start (Fig.5). Some enclaves have chilled margins against the tonalite. Some enclose a few still more mafic enclaves, as does the main mass of gabbroic diorite. Also present with the gabbroic diorite enclaves in the tonalite are other, generally more felsic varieties of microgranitoid enclave; so evidently the tonalite already carried enclaves before coming to rest against the gabbroic diorite. Many of the gabbroic diorite enclaves are elongate, with wispy or spindle ends (Fig.6), and in zones of strong flow in the tonalite, the enclaves are greatly extended (with aspect ratios of up to about 40:1) parallel to the flow-foliation in the tonalite. However, despite a strong preferred orientation of plagioclase laths, neither the tonalite nor the highly distorted enclaves show evidence of crystal strain or recrystallization (Fig.7), apart from minor warping of biotite. Therefore, the deformed, interlayered enclave/tonalite mixture is similar to Harker's "gneissic banding" (Harker, 1909, pp.340-3) and can only be satisfactorily explained by coexistence of gabbroic diorite magma and tonalite magma in a situation in which homogenization by mixing did not occur.

EXPERIMENTS ON MAGMA MIXING

Yoder (1973) showed experimentally that basaltic and rhyolitic liquids are completely miscible, but that they may stay separated by a sharp interface for at least 1-2 hours, even when saturated with water. The mafic melt tends to form lobes that are convex towards the felsic melt, as in natural situations (Figs.5, 6; Walker & Skelhorn, 1966). These shapes and the sharp interface are probably due to the higher viscosity of the strongly undercooled mafic melt.

Kouchi & Sunagawa (1982, 1983) produced gradational mixing in all proportions between small volumes of basalt and dacite melts, with linear chemical variation between the two end-members, in several hours (Kouchi & Sunagawa, 1982, pp.171-2). Mixing was most complete with higher ratios of basalt to dacite, and extensive mixing resulted in complete conversion of the basalt to andesite, leaving some unmixed dacite that was unchanged in composition. Thus, mixing of small droplets of dacite melt in basalt melt is much more effective than for droplets of basalt melt in dacite melt, so much so that for small basalt:dacite mixing ratios, interlayering of basalt and dacite melts occurs. This could be analogous to the common interlayering of mafic/intermediate glass and felsic glass in natural volcanic areas, as discussed later. It is difficult to know whether the viscosity contrasts between the basalt and dacite (both anhydrous) are the same as they would be in nature. In nature, the two magmas would come together at different temperatures, so that the mafic one would tend to chill against the felsic and so become more viscous. In the experiments the temperatures of the two melts were the same, but still the mafic melt would be more undercooled than the felsic, and so may well be more viscous. If so, the explanation of the difference in behaviour could be that felsic blobs in mafic melt are fluid enough for extensive physical mixing and chemical interchange with the mafic

melt, causing complete mixing, whereas mafic blobs in felsic melt are undercooled and so are too viscous for complete mixing. Nevertheless, chemical exchange between the droplet and surrounding melt occurs, because Kouchi & Sunagawa (1982, 1983) found that droplets changed their composition faster than the bulk basalt or dacite melt. An important aspect of the experiments was that vigorous stirring was necessary to achieve mixing, and so effective stirring - presumably mainly by convection currents, as suggested by Harker (1909) - would be necessary in nature as well.

ORIGIN OF MICROGRANITOID ENCLAVES BY MIXING AND MINGLING OF MAGMAS

The foregoing plutonic occurrences show that microgranitoid enclaves can be incorporated as blobs of more mafic magma in granitoid magma. Mingling of various magmas of a granitoid suite could help explain the compositional range of microgranitoid enclaves. Another explanation could be the mixing of felsic and more mafic magma in varying proportions, as in the experiments of Kouchi & Sunagawa (1982, 1983). The occurrence of a wide compositional range of enclaves at one locality (e.g., at Tuross Head) indicates that the mixing, if applicable, must have occurred deeper than the present level of exposure, the variety of enclaves having been incorporated in the final pulse of magma that rose to the level now exposed, where it also incorporated enclaves from the fortuitously encountered gabbroic diorite magma.

Magma mixing can explain the rarity of enclaves more felsic than the host granitoid, as droplets of felsic melt enclosed in mafic melt would disappear much more quickly than droplets of mafic melt in felsic melt (Kouchi & Sunagawa, 1982, 1983).

Harker (1909, p.354) emphasized that the enclaves "must be considered with reference, not merely to the particular rock which encloses them, but to the whole suite". That is, the enclaves may be considerably removed from their place of origin (King, 1964, p.290), which is why there is generally no obvious modification of the granitoid adjacent to a particular enclave (Thomas & Smith, 1932, p.291). Harker (1909, pp.354-5) also noted that dykes and sheets of mica lamprophyre near the Shap granite, Westmorland, England, contain large corroded grains of quartz and K-feldspar, and suggested that they "were derived from the basic lower layers of the magma-reservoir, into which some quartz and felspar sank from the overlying acid magma". Harker & Marr (1891, p.287) noted the resemblance of the rocks in these dykes and sills to the microgranitoid enclaves in the Shap granite, and therefore suggested that parts of the mafic lower layer of a magma chamber were injected to form the lamprophyric dykes, whereas other parts were carried up as enclaves in the granite. A general similarity between microgranitoid enclaves and certain dyke-rocks has already been noted, and so a common origin is reasonable. Pabst (1928, pp.362-3) mentioned dykes of biotite lamprophyre in a granitoid of the Sierra Nevada, the lamprophyre being compositionally similar to the microgranitoid enclaves.

Many of the foregoing examples of magma mingling in the plutonic environment show that the resulting enclaves generally are rounded right from their initial incorporation (Fig.5), and so magma mingling is an excellent mechanism for producing the commonly rounded shapes of microgranitoid enclaves. It also accounts well for (a) marginal chilling in some enclaves; (b) magmatic flow alignments in some enclaves; (c) distortion of enclaves during flow of the granitic magma, without grain deformation or recrystallization, the degree of elongation correlating well with the degree of flow extension in the granitoid; and (d) the increased degree of flattening of enclaves towards the margins of many plutons.

It appears to be generally true, though I don't know of any statistical, quantitative studies, that the more mafic enclaves are finer-grained than the more felsic ones. Harker (1909, p.348) attributed this to the general tendency for earlier crystallizing minerals to be finer-grained than quartz and K-feldspar. However, this argument fails, because every mineral in an enclave is typically finer-grained than its counterpart in the host granitoid. The grainsize differences can be explained by reference to Figs.13 and 14, which show the typical variation of nucleation rate ($\dot{N}$) and growth rate ($\dot{G}$) of crystals with increasing undercooling (ΔT) in freezing liquids, the chosen example having been determined experimentally for nepheline by Winkler, as reported by Shaw (1965). At a small degree of undercooling, such as would apply in the main granitoid melt, $\dot{N}$ is low and $\dot{G}$ is high (as at ΔT = 20°C in Fig.13), resulting in a coarse grainsize. However, because of the steepness of the $\dot{G}$ and $\dot{N}$ curves, even a small increase in ΔT (e.g., ΔT = 40°C) causes a large increase in $\dot{N}$, a large decrease in $\dot{G}$, and therefore a marked reduction in grainsize from near the maximum to near the minimum (Fig.14). Larger values of ΔT produce progressively finer grainsizes. The result is that, although the more mafic enclaves tend to be finer-grained because of their greater degrees of undercooling, even relatively felsic enclaves are finer-grained than their host granitoids. However, although

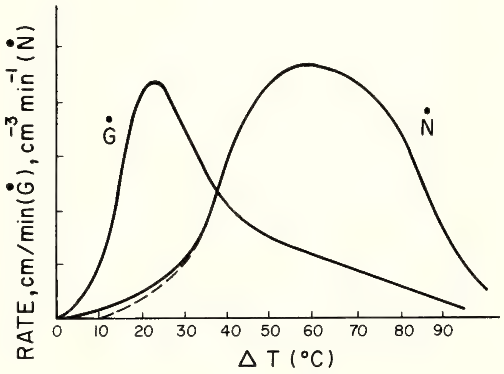

Fig. 13. Plots of nucleation rate ($\dot{N}$) and growth rate ($\dot{G}$) versus degree of undercooling (ΔT) for nepheline, determined experimentally by Winkler, as reported and slightly modified (dashed line) by Shaw (1965).

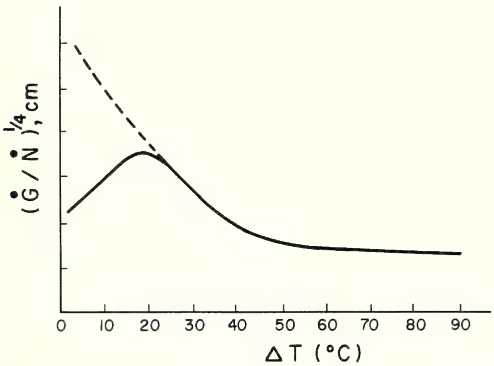

Fig. 14. Plot of grainsize variation (represented by Ġ/Ṅ) versus ΔT from the data of Fig.13 (Shaw, 1965).

temperature gradients may cause marginal chilling of enclaves in the subvolcanic environment, as discussed previously, this would be less likely in the plutonic environment, where steep temperature gradients generally could not be maintained long enough to produce chilled margins on many of the enclaves. Rapid temperature equilibration between the enclave globule and the granitoid melt would mean that the former should be uniformly more undercooled and so should crystallize to a uniformly finer-grained aggregate. Nevertheless, crystallization in some enclaves evidently was rapid enough to preserve evidence of temperature gradients in the form of chilled margins (Fig.9), as observed by Wells & Woolridge (1931).

CHEMICAL AND MINERALOGICAL CHANGES INVOLVED IN MAGMA MIXING

Harker (1909, p.345) inferred a sequence of progressive acidification of the basalt and basaltic enclaves and the basification of the granophyre in the British Tertiary suite. The basaltic fraction encloses former phenocrysts from the granophyre, namely corroded grains of alkali feldspar (which may have glass inclusions), quartz (which may be rimmed by fine-grained augite), and oligoclase with calcic overgrowths (King, 1964, p.287). The plagioclase that crystallized from the modified basalt was andesine, instead of labradorite. Both the basalt enclaves and the margin of the main body of basalt are acidified. Harker (1909, p.346) added that "independently of these reactions in place, the basalt of these sills contains occasional xenocrysts of quartz and alkali felspars, sharply contrasted with the fresh phenocrysts of labradorite, and undoubtedly brought up by the basalt magma. We have thus direct proof that the basic and acid magmas, prior to their intrusion, coexisted in subterranean reservoirs; that the lighter acid magma overlay the denser basic one; and that crystals which formed in the upper acid stratum sometimes sank into the lower basic one". King (1964, pp.289-90) noted that the xenocrysts are least corroded and more abundant in the more felsic enclaves, which is best explained by the mixing of different proportions of mafic and felsic magma before the enclaves were incorporated in the felsic host magma and transported to the site of mingling that is now exposed.

Harker (1909) and Wager *et al.* (1965) have discussed the hybridizing process responsible for the formation of the Skye "marscoite", which consists of unaltered phenocrysts of calcic andesine, with large corroded crystals of quartz and K-feldspar, in a groundmass of hornblende, oligoclase-andesine, and some interstitial quartz. The corroded quartz and K-feldspar appear to have been derived from a felsic magma, and the calcic andesine phenocrysts appear to belong to a mafic/intermediate magma. As is common in hybrid calcalkaline rocks, the corroded quartz grains are rimmed by fine-grained pyroxene, and the K-feldspar by dendritic plagioclase. Wager *et al.* (1965) ascribed the hybridization to intimate mixing of an underlying mafic/intermediate (ferrodioritic or hawaiite) magma and an overlying felsic magma in a small, high-level reservoir, in which convection currents stirred both magmas. Vigorous stirring would have been needed to produce the observed uniform distribution of phenocrysts in the marscoite, and this would also have helped mix the liquid fractions of each magma. However, homogenization sufficient to produce the almost uniform groundmass would also have been helped by diffusion. In places, marscoite passes gradually into ferrodiorite; in other places, marscoite is chilled against the felsite that is inferred to represent the felsic parent, and veins of the felsite cut the marscoite, these relationships being typical of mingling magmas, as discussed previously.

The Skye marscoite shows that intimate, effective mixing of mafic/intermediate and felsic magmas can occur, producing hybrid magma that crystallizes to form an igneous rock with the composition and petrographic characteristics of microgranitoid enclaves. It also shows that the hybrid magma and felsic magma can coexist, so that mingling and the dispersal of enclaves of mixed magma in felsic rock can be expected. The result should be microgranitoid enclaves of finer grainsize than the host granitoid, as explained previously.

Thompson (1969) showed that the ferrodiorite inferred to be the more mafic parent for the marscoite may itself be a hybrid rock, as it contains rimmed quartz xenocrysts.

Wiebe (1973) described mixing zones between chilled pillows and lenses of hornblende-bearing "basalt" and biotite leucoadamellite in composite dykes in northern Cape Breton Island, Nova Scotia. Wiebe inferred that the "basalt" solidified within 1 hour after intrusion and that most of the granitic magma solidified within 30 hours. Along the contacts between the two magmas, zones about 2 cm thick occur, in which biotite is strongly concentrated in the "basalt" and K-feldspar is absent from the adamellite. Major transfer of K, Rb, Ca, Sr and Na occurred up to a few cm across these contacts, these elements being relatively loosely

bound or relatively mobile in polymerized melts. Si, Fe, Ti, Mg, and Al were much less mobile. Near the contact, the more mafic rock is enriched in K and Rb and depleted in Na, Ca and Sr, and the adamellite shows the reverse trends. Some water also appears to have been transferred from the felsic to the more mafic melt. Concentration gradients are shallower in the "basalt" than in the adamellite, as in the experiments of Kouchi & Sunagawa (1982, 1983), indicating faster diffusion rates in the more mafic magma. Evidence of these chemical changes are absent or extremely faint along fractured "basalt"/adamellite contacts (fractured pillows); so the exchange must have occurred while both "basalt" and adamellite were partly liquid - i.e., within a few hours of intrusion. This occurrence is a clear indication of the effectiveness and rapidity of chemical interchange between felsic and more mafic magmas.

Gamble (1979) detected gradients in Na, K, Rb, Zr, Pb and Y across a sharp interface between mingled basaltic and granitic rock at Slieve Gullion, NE Ireland. The mobility of relatively less mobile elements, such as Zr and Y, indicates efficient diffusion while the two magmas were in contact. In addition, Fe^{3+}, Cr, V and Ni show gradients in the mafic component towards the mafic/felsic interface. Effective mixing in place is also indicated by the fact that mixing calculations using the compositions of mafic and felsic end-members agree with plots of major oxides versus SiO_2 across the hybrid zone.

Wiebe (1968, pp.701-2) described a stock of peraluminous (S-type) biotite-quartz monzonite with accessory cordierite and garnet near Seattle, Washington, U.S.A. Most plagioclase phenocrysts in the monzonite have corroded, zoned cores of andesine, but some phenocrysts have corroded cores of bytownite or labradorite. These cores are generally euhedral and show faint oscillatory zoning, indicating magmatic crystallization. The zoned sodic rims on these cores are typical of all the phenocrysts, but the andesine stage, represented by the cores of the more common phenocrysts, is unrepresented. This suggests that the bytownite/labradiorite cores were not in contact with the granitic magma during part of its crystallization history. These calcic cores are similar to plagioclase phenocrysts in microgranitoid enclaves, the groundmass of which consists of fine-grained quartz, feldspar, biotite and (?) cummingtonite. Conceivably, the (?) cummingtonite has replaced former orthopyroxene, which would be a likely mineral in a microgranitoid enclave of peraluminous type, as mentioned previously. The calcic plagioclase phenocrysts of the enclaves have been corroded and overgrown by plagioclase of the typical sodic rim composition where they contact the surrounding quartz monzonite.

Wiebe (1968, p.702) inferred that the calcic plagioclase cores in the granitoid were extracted from the enclaves, which he interpreted as "partially assimilated pieces of the earliest intrusions to shallow levels". An alternative interpretation is that the enclaves represent globules of hybridized mafic magma dispersed through the granitic magma, the calcic plagioclase cores having been mixed into the granitic magma during the mingling. The mingling must have occurred after the main intrusion of the magma, because only sodic rims have grown on the calcic cores.

Wiebe (1968, p.695) also observed an anorthite-rich zone or "spike", which is relatively constant in the plagioclase throughout the pluton. He ascribed the spike to mixing within the magma chamber, and added that "truncation of earlier formed zones by the spike records a period of partial resorption when the more sodic phenocrysts initially came into contact with hotter, more mafic magma" (Wiebe, 1968, p.697).

Taylor *et al.* (1980) described hybrid rocks formed by incomplete mixing of basalt and biotite-hornblende granite in composite dykes at Mount Desert Island, Maine, U.S.A. The basalt occurs mainly as pillow-like masses separated by granite, the contacts being cuspate and sharp. The basalt is chilled against the granite, and pyroxene is progressively replaced by hornblende towards the pillow margin, the replacement generally being complete in the variolitic chilled zone, where minor biotite may also occur. Taylor *et al.* (1980, p.440) attributed this replacement to hydrothermal alteration after crystallization of the basalt, during exsolution of a hydrous vapour phase by the granitic magma. However, conceivably the rimming and replacement may have occurred before complete crystallization of the basalt. Large quartz and microcline grains may occur in the basalt pillow margins (Taylor *et al.*, 1980, fig.1c, p.434).

Light grey masses ("skialiths") resembling the basalt pillows in shape and distribution are also present in the granite. The "skialiths" appear to be identical to microgranitoid enclaves in granitoid plutons. Taylor *et al.* (1980, p.441) interpreted them as the result of mixing of mafic and felsic magma at depth, prior to injection of the composite dykes, which explains their coexistence with chilled basalt pillows that do not show extensive evidence of mixing. The "skialiths" are very variable in composition and microstructure, and contain rounded mafic-rich clots of hornblende and plagioclase that may represent former blobs of more mafic magma (double enclaves). The "skialiths" consist of phenocrysts of quartz, microcline and plagioclase set in a fine-grained groundmass of quartz, microcline, zoned plagioclase, biotite, hornblende and magnetite. Much of the groundmass has a flow structure that is deflected around the phenocrysts. The groundmass plagioclase has lath-shaped calcic(An_{55}) cores with sodic (An_{15-20}) rims, and the plagioclase phenocrysts have cores of An_{26-37}. Taylor *et al.* (1980, p.436) described the margins of the phenocrysts as being "embayed", suggesting magmatic corrosion. However, they also interpreted intergrowths of groundmass minerals and phenocryst margins as indicating replacement, whereas this structure can result simply from magmatic overgrowth on phenocrysts during growth of groundmass minerals (e.g., Brammall & Harwood, 1932, fig.15).

The "skialiths" are intermediate to the basalt and granite in all major and trace element concentrations, except for Na and, in some examples, Al. The "skialiths" closely resemble the granite samples in REE distributions.

The phenocrysts in the enclaves are of similar size to the equivalent minerals in the granite, and the composition of the plagioclase in the enclaves is very similar to that of the plagioclase in the granite. However, the cores of the groundmass plagioclase in the enclaves are compositionally similar to plagioclase phenocrysts in the basalt pillows. These relationships support magma mixing as the process responsible for the material of the enclaves. A comparison of chemical compositions indicated that one particular enclave could have been produced by the mixing of about 32% basalt and 68% granite, but these proportions would be different for other enclaves.

Although the "skialiths" resemble the basalt pillows in size and shape, they do not have chilled margins, and many of their margins are more gradational than sharp. I interpret these relationships as being due to longer contact between mafic and felsic magmas at the depth of formation of the "skialiths", permitting more extensive chemical exchange (with the formation of more felsic margins) and inhibiting local chilling, though nevertheless producing an overall finer-grained, quenched rock, compared with non-hybridized gabbroid and granitoid rocks. This explanation may well account for the typically uniform grainsize of microgranitoid enclaves in granitoid plutons everywhere, as discussed previously.

Consideration of the foregoing, plus my own observations, suggests the following (no doubt oversimplified) picture for the plutonic mixing of metaluminous (I-type) felsic and more mafic magmas. Mixing should produce new magmas with variable compositions, depending on the proportions of the two initial magmas and their original compositions. Most of the mixing would occur in the melt, but if present, crystals (phenocrysts and cores of zoned crystals) may also be contributed from each magma. The more mafic magma may or may not contribute crystals of pyroxene and intermediate to somewhat calcic plagioclase, which find themselves in a more hydrous, cooler, more felsic melt than previously. The pyroxene should tend to react with the melt to form hornblende or even biotite; such reactions have been described in chilled mafic pillows enclosed in granitic rock (e.g., Taylor *et al.*, 1980) and are common in microgranitoid enclaves. The plagioclase may partly dissolve, producing corroded crystals, after which precipitation of more sodic plagioclase, both in the core embayments and in oscillatory zoned rims, would take place (e.g., Wiebe, 1968). Some relatively mafic magmas may contribute crystals of brown hornblende, which are relatively common in rocks inferred to be of hybrid origin (Didier, 1973, p.197). Presumably these should become rimmed with green hornblende.

The felsic magma may contribute crystals of quartz, K-feldspar, relatively sodic plagioclase, and biotite, possibly with hornblende. All these minerals may tend to dissolve in the hotter, more mafic hybrid magma, though this tendency may be counteracted by the tendency for more of these minerals to crystallize, owing to a decrease in water content of the hybrid melt, compared with the felsic melt. Nevertheless, the rounding of some quartz and K-feldspar phenocrysts, coupled with the rounding of some plagioclase cores, may be due to this effect. Crystallization then occurs on these corroded grains. Quartz becomes rimmed with fine-grained, mafic-rich aggregates (pyroxene or hornblende in basic and intermediate melt compositions, respectively), as described by Harker (1909). The rims probably are due to heterogeneous nucleation and enhanced crystallization rates caused by solution of the quartz, which locally undercooled the immediately adjacent melt. The corroded K-feldspar grains are commonly rimmed with oligoclase (forming a variety of rapakivi structure) which is typically dendritic, owing presumably to enchanced crystallization rates of plagioclase in the hybrid melt (Hibbard, 1981). This rim may be matched by dendritic growth zones on plagioclase crystals from the felsic component (Hibbard, 1981). After this initial corrosion and rimming, caused by the drastic but temporary instability brought about by the magma mixing (Hibbard, 1981), crystallization of quartz, K-feldspar and sodic plagioclase continues, in places forming crystallographically continuous overgrowths on the earlier corroded grains and intergrowing with groundmass minerals. In other words, the crystallization of quartz, K-feldspar and plagioclase is halted temporarily, either because these minerals are unstable in the mixed melt or, more probably, because they are present in larger amounts than those required in the equilibrium assemblage for the new (hybridized) bulk composition (Whitney, 1975, p.28).

Mixing of more mafic magma and peraluminous (S-type) granitic melts is also feasible. For example, Hill *et al.* (1981) suggested that mixing with mafic magma can explain the strontium and oxygen isotopes in a peraluminous granodiorite in SW Alaska. Presumably plagioclase, quartz and K-feldspar phenocrysts would behave similarly to those in the metaluminous situation, but crystals of clinopyroxene contributed by the mafic magma would probably react to form biotite, rather than hornblende, because of the high Al/Ca ratio of the felsic melt. Enhanced crystallization of biotite may well prevent crystallization of K-feldspar from the hybridized melt, as in microtonalitic enclaves in the Cowra Granodiorite (Vernon *et al.*, in prep.). However, because the mixing probably occurs at emplacement levels high in the crust, orthopyroxene may crystallize with the biotite (as in the microtonalitic enclaves of the Cowra Granodiorite) as predicted by the 100-200 MPa experiments of Clemens & Wall (1981). Quenching would preserve the orthopyroxene in the enclaves, whereas it invariably reacts completely with the melt to produce biotite in the surrounding granitoid. If cordierite phenocrysts are contributed by the felsic magma, they probably would be corroded in the mixed melt, because they are in excess of the amount required by the changed equilibrium. However, they eventually continue to grow in the mixed magma, as evidenced by interstitial primary cordierite in the groundmass of the Cowra microgranitoid enclaves (Vernon *et al.*, in prep.). Incidentally, if the Cowra microtonalitic enclaves result from the mixing of felsic and mafic magmas, they conform with the experimental results of Wyllie *et al.* (1976) and Wyllie (1977), which indicate that tonalitic magmas are not likely to be primary crustal melts, but may involve the addition of mafic magma to felsic magma.

The melt phase in the hybrid should crystallize more rapidly than the felsic melt, because it is

more undercooled at the prevailing conditions, as discussed previously, although it should crystallize less rapidly than a chilled melt of the more mafic parent composition. It should precipitate more biotite, hornblende and calcic plagioclase than the felsic parent, but more sodic plagioclase than the more mafic parent. Hydrous mafic minerals would be promoted by the water content, except for orthopyroxene at high temperatures in peraluminous hybrid magmas. As already noted, cordierite may precipitate from peraluminous hybrid magmas, but K-feldspar may be inhibited from crystallizing in such magmas by enhanced growth of biotite.

EXTENT AND LOCATION OF MAGMA MIXING

It remains to speculate on the extent and location of the mixing and mingling processes that could give rise to the microgranitoid enclaves. Examples of magma mingling are instructive, because they represent an arrested stage in the mixing process, but how relevant are they to the generation of microgranitoid enclaves as a whole, remembering that most exposed examples of mingling show evidence of more thorough mixing at depth?

Are examples like Tuross Head merely local indications of the kind of process involved or are they the essence of the process? A similar process, carried out repeatedly at different levels, even if quite locally, between a series of related magmas during a plutonic intrusion event, could account for the variety and possibly the number of enclaves typically seen in granitoid plutons. The magmas concerned could owe their chemical variation to magma mixing, differentiation, or any other suitable process. This is essentially magma mingling, rather than magma mixing. One difficulty with this idea is that many of the enclaves contain large grains that appear to have been inherited from either the felsic or the more mafic parent, which implies relatively thorough mixing. Also, the lamprophyric dykes that are petrographically similar to the enclaves presumably require a relatively large reservoir of hybrid magma, as envisaged by Harker (1909) and discussed more recently by Eichelberger (1978, 1980). This may also explain the numbers of enclaves better than repeated, local mingling, though this point is doubtful. The compositional variety could be explained by varying proportions of mafic and felsic components in the mixed magma, as in the mixing experiments of Kouchi & Sunagawa (1982, 1983).

The possibility of relatively large bodies of more mafic magma beneath granitic melts in high-level plutons is supported by the composition of volcanic ejecta produced in large caldera-type eruptions that probably represent the draining of large granitic melt reservoirs in the upper crust (e.g., Eichelberger, 1980).

As noted by Blake *et al.* (1965), simultaneous eruptions of felsic and more mafic magmas have occurred at many volcanic centres, such as the famous Gardiner River area and at other places in Yellowstone Park, Wyoming (Fenner, 1938, 1944; Wilcox, 1944; Hawkes, 1945; Boyd, 1961). Of particular interest is the 1912 banded pumice of Katmai, Alaska, which consists of a felsic component with 74.7% SiO_2 and a more mafic component with 60.4% SiO_2 (Fenner, 1920). This was interpreted by Williams (1954, p.326) as being due to the simultaneous eruption of rhyolite and andesite magmas, and it provides evidence, in addition to that of Crater Lake, that felsic and andesitic magmas can coexist in plutonic reservoirs.

Sparks *et al.* (1977) noted that tephra consisting of an intimate mixture of two or more contrasting magma compositions are common, the more mafic component generally occurring as bands, streaks or irregular, rounded globules. Some examples are mixtures of tholeiitic basalt and rhyolite; others are of basic andesite and rhyodacite; and still others are much closer to each other in composition. For example, in one deposit the two components have SiO_2 contents of 61.1 and 65.7%. Similarly, Walker & Skelhorn (1966) noted a set of simultaneous ejecta with SiO_2 = 57% and 64-68% and another with SiO_2 = 60% and 65%. These observations suggest that coexisting magmas can have the whole range of compositions shown by the microgranitoid enclaves and their enclosing rocks.

The common coexistence of felsic and andesitic, rather than mafic magmas is expected from the experiments of Kouchi & Sunagawa (1982, 1983) which showed that with extensive mixing of basalt and dacite melts, the basalt mixed easily and became completely converted to andesite, whereas some unaltered dacite melt remained, together with the complete range of intermediate hybrids. These experiments can explain the rarity of true mafic intrusive rocks associated with granitoid plutons, dioritic rocks being more common, and also the typical compositional range of the enclaves. They can also explain the typical presence of more mafic enclaves in granitoid rocks, because blobs of more mafic melt (even of andesitic composition) enclosed in dacitic melt did not mix easily in the experiments.

In addition, the experiments of Kouchi & Sunagawa (1982, 1983) showed that blobs of one melt enclosed in another changed their composition faster than larger masses of mafic and felsic melt in contact. Therefore, in plutons enclaves conceivably can continue to exchange components with the surrounding melt as long as they remain appreciably liquid.

Eichelberger (1978, pp.24-25) has suggested that because movement of basaltic magma is an effective means of heat transfer, it may well be the main cause of granitic magma, as suggested by Harker (1909) and Holmes (1931). Therefore mafic and felsic rocks are likely to be closely associated in space and time. Active volcanic centres erupting intermediate or felsic magmas do not have mafic vents, despite common basaltic volcanism in the surrounding region. "This can be interpreted as indicating that large, active silicic magma bodies beneath these centres trap rising basaltic magma because of the lower density of the silicic magma" (Eichelberger, 1978, p.25). The result may be that basaltic magma is forced to form sill-like bodies beneath the granitoid pluton.

This model envisages relatively large bodies of more mafic magma (not necessarily basalt, as such) underlying felsic magma (Fig.15), which is supported by the large volcanic eruptions of

rhyolitic and andesitic tephra previously mentioned. In addition, the abundant geophysical data for the Sierra Nevada are consistent with a model involving a gradational density increase into more mafic rocks within the batholith (Pitcher, 1979, p.631). Eichelberger (1978, pp.24-5) suggested that magma mixing is more likely to occur in large batches of this type, because effective convective stirring is required to produce the voluminous quantities of homogeneous hybrids, and effective convection rates depend strongly on a large size of the magma body.

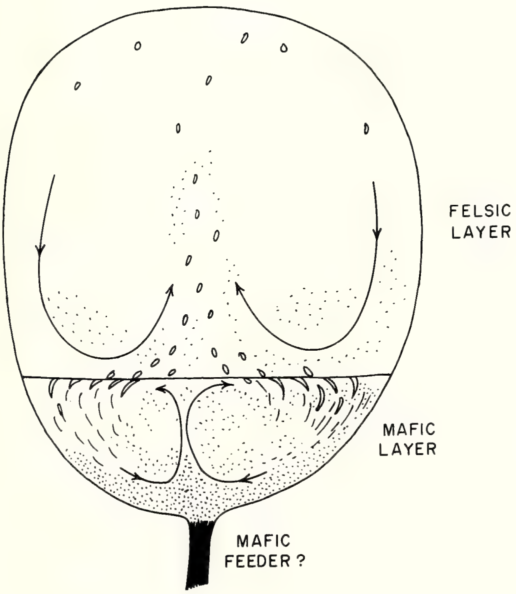

Fig. 15. Speculative sketch of a high-level plutonic magma chamber composed of an upper, convecting felsic layer and a lower, convecting, more mafic layer (though not necessarily strictly mafic, in terms of formal rock classification). More mafic magma globules collected at the interface are rounded, quenched and dispersed upwards through the felsic magma, and felsic globules are dragged down and mixed with the more mafic magma, progressively acidifying it. This should cause entrainment of progressively more felsic enclaves in the felsic magma. Dots represent accumulating crystals.

If convection of the overlying felsic magma occurs, small globules of the underlying more mafic magma may be entrained and carried up into the felsic melt (Sparks *et al.*, 1977, p.317), where they would remain intact because of the viscosity difference between them and the felsic magma. This may be the cause of many of the microgranitoid enclaves in granitoid plutons (Fig.15). If convection also occurs in the underlying mafic magma (e.g., owing to sinking of magma cooled against the chamber walls and against the felsic melt), "streaks" of felsic magma could be entrained and dragged down into the mafic magma. Entrainment of both mafic and felsic magma blobs conceivably could be effective at the magma interface, where convection currents move in opposite directions (Fig.15), as suggested by Wager *et al.* (1965) and Walker & Skelhorn (1966). The felsic streaks would be rapidly mixed with the mafic magma, as indicated by the experiments of Kouchi & Sunagawa (1982, 1983), thereby acidifying it. In this way, the globules of the more mafic magma collected by the convecting felsic magma would become progressively more felsic in composition, thereby giving rise to a range of compositions in the resulting microgranitoid enclaves. The felsic melt conceivably could become somewhat basified through chemical interaction both with the more mafic magma blobs and across the magma interface, and possibly even through physical disintegration of some enclaves, although the extent of these changes is unknown. Accumulation of crystals and enclaves conceivably may occur in the felsic magma above the more mafic layer (Fig.15), thereby accounting for the reported tendency for enclaves to be concentrated in more mafic variants of a granitoid pluton or a granitoid suite (e.g., White & Chappell, 1977).

Settling of mafic minerals and aggregates may also occur in the mafic layer of magma (Fig.15), but whether this can reduce the density of the residual melt enough to destabilize the interface and cause wholesale mingling or mixing of both magma layers, as in mafic magmas intruded by ultramafic magmas (Huppert & Sparks, 1980), is doubtful. Preliminary analogue experiments by Huppert *et al.* (1982) suggest that crystallization of a mafic layer underlying a larger, more viscous, felsic layer could reduce the density of the residual liquid in the mafic layer to such an extent that sudden convective overturning and mixing could occur, even where the viscosity ratio of the upper to the lower liquids is about 6. However, McBirney (1980) has expressed doubt that wholesale mixing of this kind can occur, in which case the bulk of the more mafic magma would remain separate from the more felsic magma until any eruption occurs. Its final composition would depend on the duration and effectiveness of the entrainment and stirring of felsic material by convection currents within the mafic layer (Fig.15), but the evidence of contrasting tephra, discussed previously, suggests that andesitic or dacitic compositions may be achieved in this lower layer. Eichelberger (1980) has suggested that crystallization of the upper parts of a hydrous basaltic layer may cause vesiculation, which would reduce the density of the more mafic layer to such an extent that the interface breaks up, and blobs of "mafic foam" rise through the overlying rocks as enclaves. Eichelberger (1980) cited vesicular enclaves of mafic and intermediate composition in volcanic rocks as evidence for his hypothesis. If this mechanism produces microgranitoid enclaves, presumably the vesicles would have to close up during entrainment and continued slow cooling in the felsic magma, as no unequivocal amygdales have been reported in them, so that the hypothesis is difficult to verify microstructurally. Some enclaves have mariolitic-like cavities, but their origin is obscure.

On the basis of simulated experiments, McBirney

(1980) suggested liquid fractionation, as an alternative to replenishment with mafic magma. He suggested that crystallization at the roof and walls of the pluton would displace lighter liquid that would rise and accumulate in a density-graded, non-convecting layer above a non-graded, convecting zone. Continued crystallization would enlarge the upper zone at the expense of the lower zone, and the interface would eventually be removed, so that the result of complete crystallization would be a granitoid pluton with concentric zoning, but without obvious vertical zoning. Eruption prior to complete crystallization could result in simultaneous tapping of both layers (producing felsic and more mafic ejecta) or even the tapping of both zones in sequence, producing magma mingling in large eruptions (e.g., Crater Lake, Oregon). The model conceivably also can explain resorbed and reverse-zoned phenocrysts, as a result of their settling through a hot zone in the upper layer of magma (McBirney, 1980, pp.370-1). However, the problem with applying this model to the origin of the microgranitoid enclaves is that it does not produce a range of magma compositions, and it does not permit convection in the felsic upper parts of the chamber.

Another alternative idea to a layered pluton is that as more mafic magma intrudes granitoid magma it breaks up into pillows or globules (Sparks *et al.*, 1977; Eichelberger, 1978). For example, Pitcher (1979, p.637) has suggested that enclave swarms occurring well away from pluton contacts may represent disintegration of synplutonic mafic dykes. The smaller of the globules would be able to rise in convection currents in the felsic melt (Sparks *et al.*, 1977). They would tend to quench, but perhaps sufficient chemical interchange could occur with the felsic melt to change their composition substantially before crystallization is complete. Eichelberger (1978) suggested that this process can produce basaltic enclaves with andesitic rims, such as occur in some volcanic ejecta. He stated that the typical volcanic enclaves are mafic to intermediate in composition, the intermediate ones containing sodic plagioclase and sometimes quartz. The enclaves in andesite are pyroxene-bearing and those in dacite are hornblende-bearing. Presumably the equivalent enclaves retained in a granitoid pluton would crystallize in more hydrous conditions, and so tend to produce hornblende, rather than pyroxene (in metaluminous plutons), as well as crystallizing completely.

Whatever process is invoked to account for the formation of the enclave globules, it is unlikely that rapid mixing of the enclaves and felsic melt will occur, owing to viscosity differences, which will be accentuated as the more mafic globules tend to chill in the abundant felsic magma.

Sparks *et al.* (1977) have suggested that injection of basaltic magma into the base of granitic magma reservoirs would rapidly produce a disequilibrium situation, by heating the felsic magma. Rise of the heated magma would cause vigorous convection, and, if saturated, the felsic magma would boil. This gas pressure may also assist convection and stirring, which would further assist mixing at the magma interface (Gamble, 1979). This exsolution of water would also be enhanced by the tendency of increasing temperature to reduce the solubility of water in the felsic melt, and by an increment of water from the crystallizing mafic melt (Sparks *et al.*, 1977). Conceivably, the gas pressure could become large enough to fracture the roof of the reservoir, so that an explosive eruption occurs (Sparks *et al.*, 1977). If this process occurred to a smaller extent, perhaps a pressure-quenched rind could be formed below the roof, in zones where the pressure was released by fracturing (Vernon & Flood, 1982). Therefore, the process of magma mixing and pressure quenching in granitoid plutons could be genetically related, and both could produce magmatic material for microgranitoid enclaves. The intrusion of mafic magma into the base of a granitoid pluton is thus an effective way of inducing vigorous convection, and, as noted by Pitcher (1979, p.638) such mobile convecting plutons are the most likely producers of silicic volcanic rocks.

CONCLUSIONS

Metaluminous granitoid plutons show little or no microstructural evidence of restite, and clear evidence of restite in peraluminous granitoids is restricted to those foliated metasedimentary xenoliths and xenocrysts that show mineralogical evidence of high pressures.

The rounded microgranitoid enclaves (autoliths) that are abundant in both metaluminous and peraluminous granitoid plutons show features that are most completely explained by quenching of magma in the plutonic environment, brought about by mingling of globules of more mafic magma (the enclaves) with felsic magma (the granitoid host). The origin of the globule magmas remains somewhat speculative, but the enclaves show features suggestive of hybrid magmas, in which case, most of the material for the enclaves may be due to magma mixing processes at locations distant from the site of mingling now exposed.

Quenched magma from earlier minor intrusions or from intrusions of more mafic magmas into the main pluton are feasible sources of magma for the microgranitoid enclaves. So is magma from pressure-quenching, provided the evidence of hybridism can be explained by the process. Disruption of solid fragments of quenched material can account for angular enclaves, as can fracturing of quenching magma by sufficiently rapid application of stress.

The lack of microstructural evidence of restite in high-level granitoid plutons, the evidence of coexisting magmas and the mineralogical evidence of magma mixing in the microgranitoid enclaves, suggest that magma mixing should be considered seriously as a contributing factor for those chemical variations in granitoid plutons that are indicative of mixing processes.

ACKNOWLEDGEMENTS

I thank Dick Flood for many stimulating discussions and ideas throughout our joint research project on granitoid microstructures, and for critically reviewing the paper. I also thank Bill D'Arcy for much technical help. The work has been supported by the Australian Research Grant

Scheme and Macquarie University.

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(Manuscript received 7.11.83)

Journal and Proceedings, Royal Society of New South Wales, Vol. 116, pp. 105-117, 1983
ISSN 0035-9173/83/020105 — 14 $4.00/1

Stratigraphy and Sedimentation of the Late Permian Illawarra Coal Measures in the Western Coalfield, Sydney Basin, New South Wales*

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ABSTRACT. After an extensive examination of data from boreholes recently sunk in the Western Coalfield, a workable stratigraphic subdivision of the Illawarra Coal Measures has been achieved, consisting of four subgroups and sixteen formations. The Cullen Bullen Subgroup, which occurs near the base of the sequence is peculiar to the western margin of the basin, and the remainder of the sequence exhibits considerable similarity to the well known southern coalfield stratigraphy.

The bulk of the sequence in the Western Coalfield is made up on non coal-bearing units of the Charbon Subgroup. These consist mainly of laminated and burrowed mudstones (Baal Bone Formation) containing acritarchs and marine foraminifera. They have a relatively high boron content and have been interpreted as interdistributary bay and pro-delta sediments. These beds are overlain by a coarsening-upwards sandstone (Angus Place Sandstone) and these two units together form a significant lithofacies association which is recognisable on a basin-wide scale. Their equivalents in the Hunter Valley are the Watts Sandstone and the Denman Formation, and in the Southern Coalfield the Darkes Forest Sandstone and Bargo Claystone.

INTRODUCTION

The Western Coalfield of the Sydney Basin is centred on the City of Lithgow approximately 105 km west of Sydney (see Figure 1). Coal was first discovered in the area here in 1824, and continuous production commenced in 1868. The area currently produces in excess of 6.3 million tonnes of coal per annum.

The geographical extent of the area of investigation covers some 1120 km^2 of the upper Blue Mountains, a deeply dissected plateau of Triassic sandstone much of which is at an elevation of about 1000 metres above sea level. The low-lying areas of Lithgow and Wallerawang Valleys, at about 600 to 900 metres elevation, contain outcrops of the Illawarra Coal Measures and underlying marine Shoalhaven Group. These and adjacent valleys are drained by streams which eventually flow eastwards through the spectacular gorges of the Cox, Grose, Wolgan and Capertee Rivers to join the Nepean-Hawkesbury system. The access to exposures of the coal measure sediments within the area is afforded by these deeply incised river valleys.

Over the last 80 years, there have been surprisingly few workers who have attempted a synthesis of data for the Western Coalfield. The early work by Carne (1908) still stands as a monument of thoroughness to the diligent workers involved. In the immediate post-war years, the work of Rayner (1954, 1956) is significant, and this was later followed by Branagan (1960). The geology of the Western Coalfield has been recently summarised by Morris (1975), and other contributors to geology relevant to the Western Coalfield include the works of Goldbery (1972), Bembrick and Holmes (1972) and Cox et al (1980). Regional geological mapping at a scale of 1:50,000 has been conducted over parts of the Western Coalfield by Bembrick and Goldbery during the period 1967-1973. Some general geological maps by Carne (1908) cover this area of the Sydney 1:250,000 geological sheet. However, few outcrop areas have been mapped in detail (see Branagan, 1960).

The basic data upon which this investigation is based are coal exploration bores that have been fully cored through the Illawarra Coal Measures. Some 30 odd bores lie on the Bungleboori 1:50,000 sheet and nearly 400 on the adjoining Lithgow Sheet. Records of most of these bores consist of a written log and core samples, and graphic borelogs have been drawn up for nearly 200 selected boreholes to interpret the stratigraphy. The borehole information has been supplemented by examination of opencuts and outcrops, by air photo interpretation and by detailed measurement of stratigraphic sections in field exposures. Available bore core has also been examined to determine, in greater detail, the lithofacies, sedimentary structures and depositional environments represented.

STRATIGRAPHIC NOMENCLATURE

The coal-bearing sequence in this area was first referred to as the "Wallerawang Coal Measures" by Stephens (1883). The first use of the term "Lithgow Coal Measures" is attributed to David and Stonier (1890), but the term was not generally used at that time. The term "Western Coal Measures" (Carne, 1908) was popular until the early 1950's and in 1957, McElroy reintroduced the term "Lithgow Coal Measures". This term remained in use until it was superseded by the term "Illawarra Coal Measures" as described by Bryan et al (1966).

Terms such as the "Marrangaroo Conglomerate" and "Lithgow Seam" were in use by 1894 and probably earlier. Names such as "Irondale Seam", "Dirty Seam" and "Katoomba Seam" were next to make their appearance (Carne, 1908), although, again, they were probably in general use much earlier.

Most of the remaining names now in general use

* Communicated by H. Basden

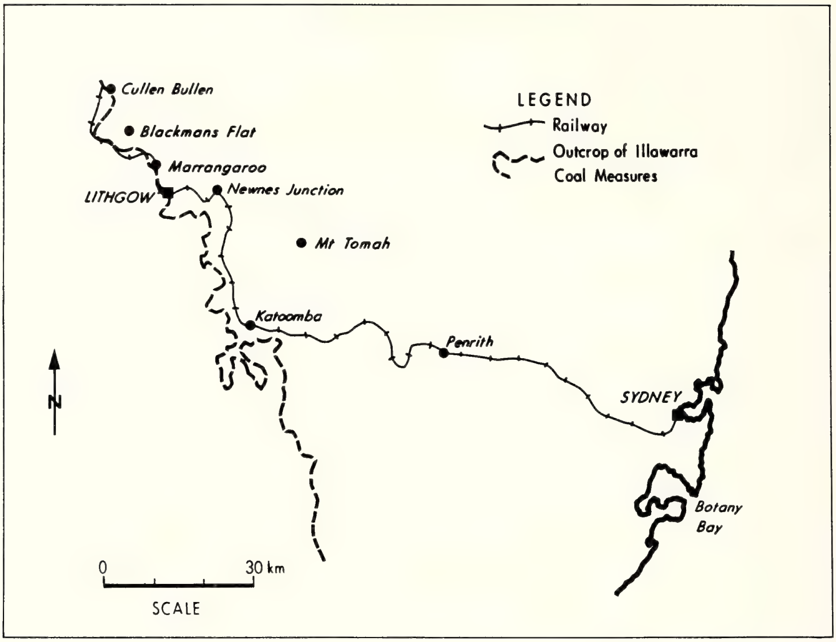


Fig. 1. Locality sketch showing area of study in relation to Sydney.

TABLE 1

ILLAWARRA COAL MEASURES - WESTERN COALFIELD

PREVIOUS NOMENCLATURE*

(After Morris 1975, Goldbery 1972 and Bembrick, 1980)

			Katoomba Seam
			Unnamed Section
			Woodford Seam
			Burragorang Claystone
			Middle River Seam
	Charbon		Unnamed Section
	Subgroup		Ivanhoe Sandstone
			Irondale/Wolgan Seam
Illawarra			Bunnyong Sandstone
Coal			Unnamed Section
Measures			Lidsdale Seam
			Blackman Flat Conglomerate
			Lithgow Seam
			Marrangaroo Conglomerate
	Nile	(	Gundangaroo Fromation
	Subgoup	(	Coorongooba Creek Sandstone
		(	Mt. Marsdan Claystone

* In the present study, this nomenclature has been essentially maintained, but has been added to and re-grouped so as to redefine the Charbon Subgroup. Table 2 shows the new nomenclature proposed as a result of this investigation. This has now been accepted by the stratigraphic nomenclature committee of the Geological Society of Australia.

TABLE 2

ILLAWARRA COAL MEASURES - WESTERN COALFIELD

NEW NOMENCLATURE

(Goldbery 1972 and Bembrick, this paper)

Wallerawang Subgroup	(Farmers Creek Formation	(Katoomba Coal Member
	(	(Woodford Coal Member
	(	(Burragorang Claystone Member
	(	(Middle River Coal Member
	(	
	(	
	(Gap Sandstone	
Charbon Subgroup	(State Mine Creek Formation	(Moolarben Coal Member
	(Angus Place Sandstone	
	(Baal Bone Formation	
	(Glen Davis Formation	
	(Newnes Formation	(Ivanhoe Sandstone Member
	(	
	(Irondale Coal	
	(Long Swamp Formation	(Bunnyong Sandstone Member
Cullen Bullen Subgroup	(Lidsdale Coal	
	(Blackmans Flat Conglomerate	
	(Lithgow Coal	
	(Marrangaroo Conglomerate	
Nile Subgroup	(Gundangaroo Formation	
	(Coorongooba Creek Sandstone	
	(Mt. Marsden Claystone	

in the Western Coalfield date from the work of Rayner in the period from 1948 to 1956. However, several names were introduced by McElroy (1957), namely the "Woodford Seam", "Middle River Seam" and "Blackmans Flat Conglomerate".

The recognition of a partially coal-bearing sequence between the Berry Siltstone and the traditional base of the Illawarra Coal Measures in the Western Coalfield (The Marrangaroo Conglomerate) was formalised by Goldbery (1972). This lower sequence had previously been identified in the Southwestern and Western Coalfields (Whiting and Relph, 1969). Thus, in the Western Coalfield, the Illawarra Coal Measures were split into the upper, Charbon Subgroup and the lower, Nile Subgroup.

The previous nomenclature applicable to the Illawarra Coal Measures of the Western Coalfield is shown in Table 1.

STRATIGRAPHY

The overall stratigraphy of the Western Blue Mountains, at the margin of the Sydney Basin, has been summarised elsewhere (Goldbery, 1972; Bembrick, 1980) and need not be repeated here. Goldbery (1972) and Bembrick and Holmes (1972) have adequately described the Nile Subgroup, and this will not be described further in the present paper.

The following descriptions are of new and redefined units in what was formerly the Charbon Subgroup of the Illawarra Coal Measures. As shown in Table 2, this former subgroup is now split into three well defined, easily recognisable and distinctive subgroups, namely the Wallerawang Subgroup, the Charbon Subgroup and the Cullen Bullen Subgroup. These three subgroups and their 13 constitutent formations are briefly described below. No attempt has been made at this stage to formally describe and define the members within these formations, although brief mention is made of the more important of these (see Figures 2 and 3).

Formal definitions of these formations and subgroups have been accepted by the N.S.W. Sub-Committee on Stratigraphic Nomenclature (Geological Society of Australia) and by the Western Coalfield Sub-Committee of the N.S.W. Standing Committee on Coalfield Nomenclature. These formal definitions will be published in the Records of The Geological Survey of New South Wales.

CULLEN BULLEN SUBGROUP

This sequence is made up of conglomerates, pebbly lithic-quartz sandstones and thick economic coal seams. The conglomeratic units are extremely variable in thickness, and on a broad scale form lobe-shaped wedges, thinning away from the basin

margin. The pebbly sandstones distal to the conglomerate wedges are relatively uniform in thickness as are the interbedded coals. In localised areas adjacent to the basin margin, however, the coals are split by the conglomerate wedges.

The Cullen Bullen Subgroup contains, in descending order, the following units:-

Unnamed sandstone unit (sporadically developed)
Lidsdale Coal
Blackmans Flat Conglomerate
Lithgow Coal
Marrangaroo Conglomerate

The Lidsdale and Lithgow coals merge and become one thick coaly unit to the northeast away from the basin margin, and also in the north along the margin towards Kandos and Ulan. The intervening Blackmans Flat Conglomerate rapidly wedges out to become represented by a fine grained clastic split in this combined coal unit.

The broad relationships of these units and their nomenclature are illustrated diagrammatically in Figure 4. Near the margin of the basin, this subgroup is composed almost totally of conglomerate and is more than 46 metres thick. However, over much of the western margin, the subgroup is represented only by the Marrangaroo Conglomerate and the overlying Lithgow Coal (actually a Lithgow/Lidsdale Coal combination). The typical thickness of the widespread pebbly sandstone of the Marrangaroo Conglomerate is 3 to 4 metres, and for the overlying coal, 2 to 3 metres.

On the Newnes Plateau in ELN DDH 31 (see Figure 5), the Cullen Bullen Subgroup consists only of the Marrangaroo Conglomerate and the Lithgow Coal. It has a total thickness of around 10 metres in this area.

Marrangaroo Conglomerate

The Marrangaroo Conglomerate is a widespread and persistent unit in the Western Coalfield, with equivalents in the South-Western Coalfield (the Higgins Creek Conglomerate, Whiting and Relph, 1969) and in the Ulan area. The name is one of the oldest terms used in the Western Coalfield (Stephens, 1883).

This unit is composed of medium to coarse grained pebbly, quartz-lithic sandstone with minor mudstone beds. Locally it becomes a (dominantly quartzose) pebble and cobble conglomerate. A few coaly stringers may be present. The unit displays thick bedding and high to medium-angle planar crossbedding, often fining upwards in several subunits. It is confirmably overlain by the Lithgow Coal, but has a sharp, locally disconformable, basal contact with either the underlying coaly sediments of the Nile Subgroup or the sandy siltstones of the Berry Siltstone. The thickness ranges up to 16 metres, but is locally very variable along strike, especially close to the western margin of the basin.

Lithgow Coal

Although not clear from the published record (Carne, 1908), the Lithgow Coal is probably the earliest named bed with the Western Coalfield. It is a well developed and persistent dull coal seam, and is the major economic coal mined in the area. Details on the seam section, petrology, analyses etc. are given by Morris (1975). The Lithgow Coal has a remarkable persistence when traced along strike close to the western margin of the basin, and lithological equivalents may be recognised in the South-Western Coalfield (Kooloo Seam) and the Southern Coalfield (Woonona Coal Member). The coal is much less persistent, however, and in places unrecognisable, when traced (in subsurface) away from the margin towards the central parts of the Sydney Basin.

The formation called herein the Lithgow Coal also contains minor beds of carbonaceous claystone, mudstone, sandstone and oil shale. A maximum thickness of 9 metres is recorded for the unit. It is conformably overlain by either the Blackmans Flat Conglomerate or the Long Swamp Formation. The unit lenses out westward between lobes of the Marrangaroo and Blackmans Flat Conglomerates, but eastwards, away from the basin margins, the Blackmans Flat Conglomerate wedges out and the Lidsdale Coal (the latter's lateral equivalent) rests directly on top of the Lithgow Coal. Where no marker exists to separate the two units, the whole coaly unit in this case is regarded as the Lithgow Coal alone.

Blackmans Flat Conglomerate

The Blackmans Flat Conglomerate is a relatively new unit in the Western Coalfield (McElroy, 1957), although previous workers (Rayner, 1955) do refer to an "Upper Marrangaroo Sandstone". The unit is generally restricted to the western margin of the Western Coalfield. It is much more restricted in distribution and more variable in thickness (up to 20 m) than the Marrangaroo Conglomerate, which it strongly resembles as a lithofacies. The unit is conformably overlain by the Lidsdale Coal and generally has a sharp, often disconformable contact with the underlying Lithgow Coal. It merges with the Marrangaroo Conglomerate close to the western margin of the basin, where the intervening Lithgow Coal cannot be recognised.

Lidsdale Coal

The term "Lidsdale Seam" appears to have first been used by Taylor (1954) for the coal which is split from the Lithgow Coal by the Blackmans Flat Conglomerate. The unit comprises dull coal, carbonaceous claystone and mudstone, and is restricted to the margin of the Sydney Basin within the Western Coalfield. The Lidsdale Coal is up to 5 metres in thickness. It is generally conformably overlain by the Long Swamp Formation and is underlain by the Blackmans Flat Conglomerate, but where the latter is absent, the lateral equivalents of the Lidsdale Coal and included with the Lithgow Coal.

CHARBON SUBGROUP

Originally defined by Goldbery (1972) to encompass all of the units from the Marrangaroo Conglomerate to the Katoomba Seam, the Charbon

Subgroup is here re-defined as the interval between the top of the Cullen Bullen Subgroup and the base of the Gap Sandstone.

This sequence consists of thin sandstone and interbedded mudstones, some of which are laminated and bioturbated. Almost all of the sandstones are fine grained, have gradational bases and coarsen upwards, forming the uppermost beds of broader scale coarsening-upward successions.

Few coals occur in this sequence, but those that do are thin and localised. They are seldom persistent on a coalfield-wide scale. Within the Glen Davis Formation are several thin oil shales or torbanite seams and these have been mined in the past at Newnes and Glen Davis, where they are locally more thickly developed.

The Irondale Coal extends from the western outcrops into the Wolgan Valley area where it was called the "Wolgan Seam" (Cox et al., 1980). It is a relatively good coking coal in that area, the only one in the western coalfield. The only other significant coal horizon within this subgroup is the Moolarben Coal Member, which has its maximum development in the Ulan area.

Two units within the Charbon Subgroup are believed to be of major significance for basin-wide correlation. These are the coarsening-up beds of the persistent Angus Place Sandstone and the associated underlying Baal Bone Formation. The Moolarben Coal Member commonly caps the Angus Place Sandstone.

In the deep bore ELN DDH 31, located 12.5 km east of Cullen Bullen, the Charbon Subgroup is 80.5 metres in total thickness (see Figure 5). In areas nearer the basin margin the thickness is nearly half this figure - e.g. 47 metres in Ivanhoe Colliery DDH1, 5 km west of Blackmans Flat.

Long Swamp Formation

The Long Swamp Formation, named herein, is conformably overlain by the Irondale Coal and underlain by units of the Cullen Bullen Subgroup. It consists of claystone, mudstone and siltstone, commonly inter-laminated and thinly interbedded. Some beds show well developed flaser bedding while bioturbation ranges from common to intense in some horizons. Sporadic acritarchs are also found (McMinn, pers. comm.). Distinctive features of this unit are the occurrence of thin quartz-lithic sandstone beds, which commonly coarsen upwards, and the presence of sporadic "dropstones" within the argillaceous horizons. The topmost coarsening upwards sandstone unit (usually the thickest and most persistent) is the Bunnyong Sandstone Member (the lower Bunnyong Sandstone (undefined) of Rayner (1956) and the Bunnyong Sandstone (undefined) of Branagan (1960)). Also common within the argillaceous horizons are lenses and layers of sideritic ironstone which weather to a characteristic reddish-brown tone, and buff coloured limonitic concretions displaying an "onion-skin" structure. In places some fining-upwards sandstone units also occur, with associated thin coal beds.

The maximum recorded thickness of the Long Swamp Formation is 56 m in Wancol-Lithgow DDH 5, 25 km north of Newnes Junction.

Irondale Coal

The Irondale Coal is a relatively thin (average about 1.3 m), but persistent and widespread coaly unit found throughout the Western Coalfield. Locally (e.g. at Ivanhoe Colliery and in the Wolgan Valley) it may thicken to 3.5 metres and become of economic importance (Cox et al., 1980). The unit rests conformably on the Bunnyong Sandstone Member of the Long Swamp Formation, and is commonly underlain by a thin, pallid mudstone or sandstone "seat earth" containing abundant black carbonaceous root traces (cf. *Vertebraria* sp).

A detailed description is not attempted here, except to note that the unit comprises dull and bright coal commonly separated by "Stone" bands into four coal plies. Generally better quality (lower ash) coal occurs in the top plies, and hence the unit exhibits a distinctive profile on density logs. In the Wolgan Valley area the unit has been referred to as the Wolgan Seam and has been described as a coking coal (Cox et al., 1980). This horizon is subject to rapid lateral variations in lithology near the basin margin, however, and there sandstone is in places the dominant lithofacies of the unit.

Newnes Formation

Named from an historic mining town in the Wolgan Valley, the Newnes Formation as a whole is one of the most persistent and easily recognisable rock units in the Illawarra Coal Measures of the Western Coalfield. It consists of a fine grained, quartz-lithic sandstone, underlain by a thinly interbedded and laminated mudstone, siltstone and claystone interval. The uppermost sandstone section commonly coarsens upward and the underlying lithologies are often sparsely bioturbated.

The maximum recorded thickness for the unit is 14.5 metres in Elcom Birds Rock DDH 5, 12 km north of Newnes Junction. The Newnes Formation is conformably overlain by the Glen Davis Formation, and in very localised areas near the western margin of the basin the Ivanhoe Sandstone Member occurs at the base. This latter unit is a generally thin, pebbly, quartz-lithic sandstone within the Newnes Formation, which fines upwards and has a sharp, locally disconformable, basal contact with the underlying Irondale Coal.

Glen Davis Formation

Again named after an historic oil-shale mining locality, this formation in places contains thin, locally persistent horizons of boghead coal or torbanite. The maximum recorded thickness is 13 metres in Wancol Lithgow-Newnes DDH 1, 5 km north-east of Newnes Junction, but both the thickness and the contained lithofacies vary considerable. The unit is commonly made up of claystone (some carbonaceous), minor siltstone and mudstone with thin coal and sandstones. Sporadic developments of siliceous claystone and oil shale also occur within the unit. The thin sandstone beds where present, commonly fine downwards. The argillaceous sediments are bioturbated in part and a few acritarchs have

been recovered from the unit (McMinn, 1980). Near the western outcrop areas a coal at the base of this formation thickens locally (e.g. at Ivanhoe Colliery and Running Stream), and has been called the "Upper Irondale Seam" by Carne, (1908).

Baal Bone Formation

Named after Baal Bone Gap, north of Ben Bullen, the Baal Bone Formation makes up the bulk of the coal-barren sediments of the re-defined Charbon Subgroup. It is, in fact, a part of the sequence generally termed "The Barren Shales" by drillers and some local geologists. The maximum thickness of this unit is at least 53 metres in Mt. Tomah DDH 1. Equivalent lithofacies are known in the southern coalfield, and in the Ulan and Putty areas. In the Singleton Supergroup of the Hunter Valley, the equivalent lithofacies is known as the Denman Formation.

The Baal Bone Formation is dominated by thinly interbedded and interlaminated mudstone, siltstone and claystone, with very minor sandstone. Sporadic occurrences of thin coaly stringers are also known as well as some possible oil shales. Bioturbation is common in the lutite beds, and ranges from moderate to intense. On a broad scale the unit generally coarsens upwards. Acritarchs are relatively common and arenaceous foraminifera have been recovered from these sediments (Scheibnerova, pers. comm.). In common with other argillaceous units of the Charbon Subgroup, the Baal Bone Formation has a higher than average boron content (Swaine, Pers. Comm.). Isolated clasts, (interpreted as "dropstones) and pebble clusters are relatively common within this unit.

Angus Place Sandstone

The fine grained, quartz-lithic sandstone interval that makes up the Angus Place Sandstone is identified by its sharp top and gradational base and by its overall coarsening upward nature. The sandstone has calcareous cement in places, and exhibits low angle cross bedding and sporadic burrows. Equivalent lithofacies are recognised in the Southern Coalfield (Darkes Forest Sandstone), in the Ulan area and in the Singleton Supergroup (Watts Sandstone) of the Upper Hunter Valley. The maximum recorded thickness in the Western Coalfield is 15.5 metres in Elcom Lithgow-Newnes DDH 20, 10 km north of Lithgow. This unit, together with the underlying Baal Bone Formation, makes up a distinctive and easily recognisable coarsening-upwards interval which effectively splits the coal measures into two, an upper and a lower coal-bearing succession.

State Mine Creek Formation

The State Mine Creek Formation varies considerably in thickness (the Maximum recorded is 31.5 m in Mt. Tomah DDH 1) and in its contained lithologies. It is completely or partially eroded in some areas by the overlying Gap Sandstone. The lithofacies present include claystone, mudstone and siltstone; often thinly interbedded. Minor sandstone and coal are present locally.

The most persistent unit within this formation is the Moolarben Coal Member at the base. This thin coal, conformably overlying the Angus Place Sandstone, is widespread also on the western margin of the basin, where its persistence and characteristic signature on a density log make it useful for correlation purposes. Locally, such as in the area near Ulan, it reaches 3.5 metres in thickness, but more characteristically, in the Lithgow area, it is only one metre or less. It may deteriorate in places to only a thin coaly stringer, but rarely is it completely absent from the sequence.

WALLERAWANG SUBGROUP

The base of the Wallerawang Subgroup is marked by one of the major marker horizons of the Western Coalfield, the Gap Sandstone. The overlying Farmers Creek Formation includes the Middle River Coal Member and the Burragorang Claystone Member. The latter is prominent in outcrop, but less so in cored boreholes, particularly as the distance from the basin margin increases. The lack of a recognisable Burragorang Claystone Member means that this formation mostly consists of a number of thin coals and claystones to which it is very difficult, and probably misleading, to assign names to individual members. The lower part of the Middle River Coal Member usually displays a characteristic seam section, but above this level, many thin coals split and merge and the unit exhibits a great degree of lateral variability in its internal stratigraphy.

The Farmers Creek Formation usually contains claystones commonly referred to as 'cherty', siliceous, or (?)tuffaceous, and these appear to become more common further into the basin. Where the unit crosses the Mt. Tomah Monocline, 25 km east of Lithgow, it thickens rapidly and the proportion of clastics (mainly thought to be tuffaceous claystones) increases markedly.

The total thickness of the Wallerawang Subgroup in ELN DDH 31 is 26.6 metres and the stratigraphy of the unit in this bore is shown in Figure 5.

The top of the Illawarra Coal Measures (as a group) is currently recognised by the topmost occurrence of coal or carbonaceous sediments below the lowermost massive sandstone of the Narrabeen Group (usually the Clwydd Sandstone Member of the Caley Formation). However, it should also be noted that the top of the Permian System in the Western Coalfield (on the basis of palynological data) in fact occurs near the top of the Caley Formation (Helby, 1973).

Gap Sandstone

Named after Brown's Gap between the Lithgow and the Hartley Valleys, this sandstone is a distinctive medium and fine grained, sporadically coarse and pebbly, quartz-lithic sandstone. Medium angle, planar and trough cross bedding are common, and the unit fines upwards to a thinly bedded sandstone and mudstone interval. Sporadic fossil logs and woody fragments occur, generally not far about the sharp, erosive base of the unit.

The Gap Sandstone varies considerably in thickness, and in places can be seen to truncate the entire State Mine Creek Formation and part or all of the underlying Angus Place Sandstone. Its maximum recorded thickness is 13.5 metres in Wancol

Lithgow DDH 26, 10 km north of Lithgow. Where it lies immediately on top of the Angus Place Sandstone, the two units can often be differentiated by the erosive basal contact, the coarser (occasionally pebbly) fining-upwards nature and the steeper dipping crossbeds of the Gap Sandstone.

Farmers Creek Formation

The Farmers Creek Formation has a maximum recorded thickness of 97 metres in Mt. Tomah DDH 1. It consists of claystone, carbonaceous shale, coal, mudstone, siltstone, sandstone, siliceous claystone (?tuff) and oil shale. The unit includes the Katoomba Coal Member, the Burragorang Claystone Member and, at the base, the Middle River Coal Member.

The unit contains a variable number of coal horizons, particularly in that part of the sequence above the Middle River Coal Member, and considerable splitting and coalescence of these coal beds occurs. The Katoomba Coal Member, the topmost named unit of the Illawarra Coal Measures, is not always the topmost coal of the sequence. Examination and correlation of borehole date in both Lithgow and Ulan areas shows that the Farmers Creek Formation is overlain with a low-angle regional unconformity by the Late Permian beds of the lowermost Narrabeen Group (cf. Helby, 1970, p. 393). Where the Katoomba Coal Member has not been developed, or has been removed by erosion before deposition of the Narrabeen Group, one of the lower coal beds in the Farmers Creek Formation marks the top of the Illawarra Coal Measures. In parts of the Ulan area, to the north, the equivalent lithofacies interval to the Farmers Creek Formation has been almost entirely eroded prior to deposition of the sandstones and conglomerates of the Narrabeen Group (Shiels and Kirby, 1977; Bembrick, 1979b).

SEDIMENTATION

A detailed discussion of the sedimentation and interpreted depositional environments of each stratigraphic unit in the Illawarra Coal Measures is beyong the scope of this paper. An attempt is made, however, to focus on some of the highlights deduced from the present study. To set this in context, a brief description of sedimentation in the marine Shoalhaven Group, which underlies the Illawarra Coal Measures, is presented as well.

Shoalhaven Group

On the western margin of the Sydney Basin, the Snapper Point Formation of the Shoalhaven Group represents a sandy transgressive shoreline facies overlain by the deeper, shelf deposits of the Berry Siltstone. The conglomerate of the Megalong Conglomerate facies (basal units within the Snapper Point Formation) are probably the result of fluvial channel deposition (possibly fluvio-glacial - Herbert, 1972) in basement topographic lows prior to the marine transgression. The upper part of the Berry Siltstone shows regressive characteristics with the development of a sandy (in part deltaic) shoreline complex which forms the top of the Shoalhaven Group (Bowman, 1980).

Illawarra Coal Measures

The four subgroups which comprise the Illawarra Coal Measures in the Western Coalfield are genetically related lithofacies associations which are distinctive along the western margin of the Sydney Basin. Some units, however, appear to represent more basin-wide depositional episodes, possibly related to eustatic changes in sea level.

Nile Subgroup

The lower units of the Nile Subgroup represent the waning phases of the marine sedimentation that followed the major regression as the upper Shoalhaven Group was deposited. The Mt. Marsden Claystone represents marine influenced sedimentation, possibly in a restricted lagoonal environment, with dolomitic limestone nodules and lenses being a prominent feature. The overlying Coorongooba Creek Sandstone (calcareous in part) may represent a beach facies transitional to the onset of fluviodeltaic (coal-bearing) sedimentation in the Gundangaroo Formation.

Cullen Bullen Subgroup

The lowermost widespread fluvial units of the Illawarra Coal Measures occur in the Cullen Bullen Subgroup. The Marrangaroo and Blackmans Flat Conglomerates appear locally to consist of lobes of fluvial, braided channel deposits with coal-bearing sediments in inter-lobe areas. Elsewhere, this subgroup consists of fluvial channel sands and coal-bearing overbank and backswamp deposits. Major economic coals occur in these depositional environments, and historically this part of the sequence has been of major economic importance in the viability of the Western Coalfield. However, on tracing the Cullen Bullen Subgroup to the east by means of borehole data, it became apparent that the major part of this facies is peculiar to the western margin of the basin, if not to the Western Coalfield alone. The one noticeable exception to this is the Lithgow Coal which, because of its distinctive dull nature, has lithological equivalents which are recognised as far afield as the Ulan area (Ulan Seam), Upper Hunter Valley (Bayswater Seam) and the Gunnedah area (Hoskissons Seam, cf. Hunt, 1981; and 1982, Table 1). Palynological evidence suggests that at least in some instances, these lithological equivalents may also be time-equivalent (McMinn, 1981, 1982).

Charbon Subgroup

The bulk of the sequence in the Western Coalfield is made up of the re-defined Charbon Subgroup. This unit consists of a complex of lower delta plain deposits and relatively thin, but areally extensive coals amongst large, coal-barren intervals. Some of the coals are locally of much higher quality than in the underlying Cullen Bullen Subgroup, and oil shales within this part of the sequence have also been of economic importance.

The features which characterise the Charbon Subgroup, apart from its relative lack of coals, include extensive bioturbation, laminated and flaser bedded sediments, isolated clast clusters and "dropstones", sporadic thin (a few cm) white claystone (?tuff) bands and relatively thin fine

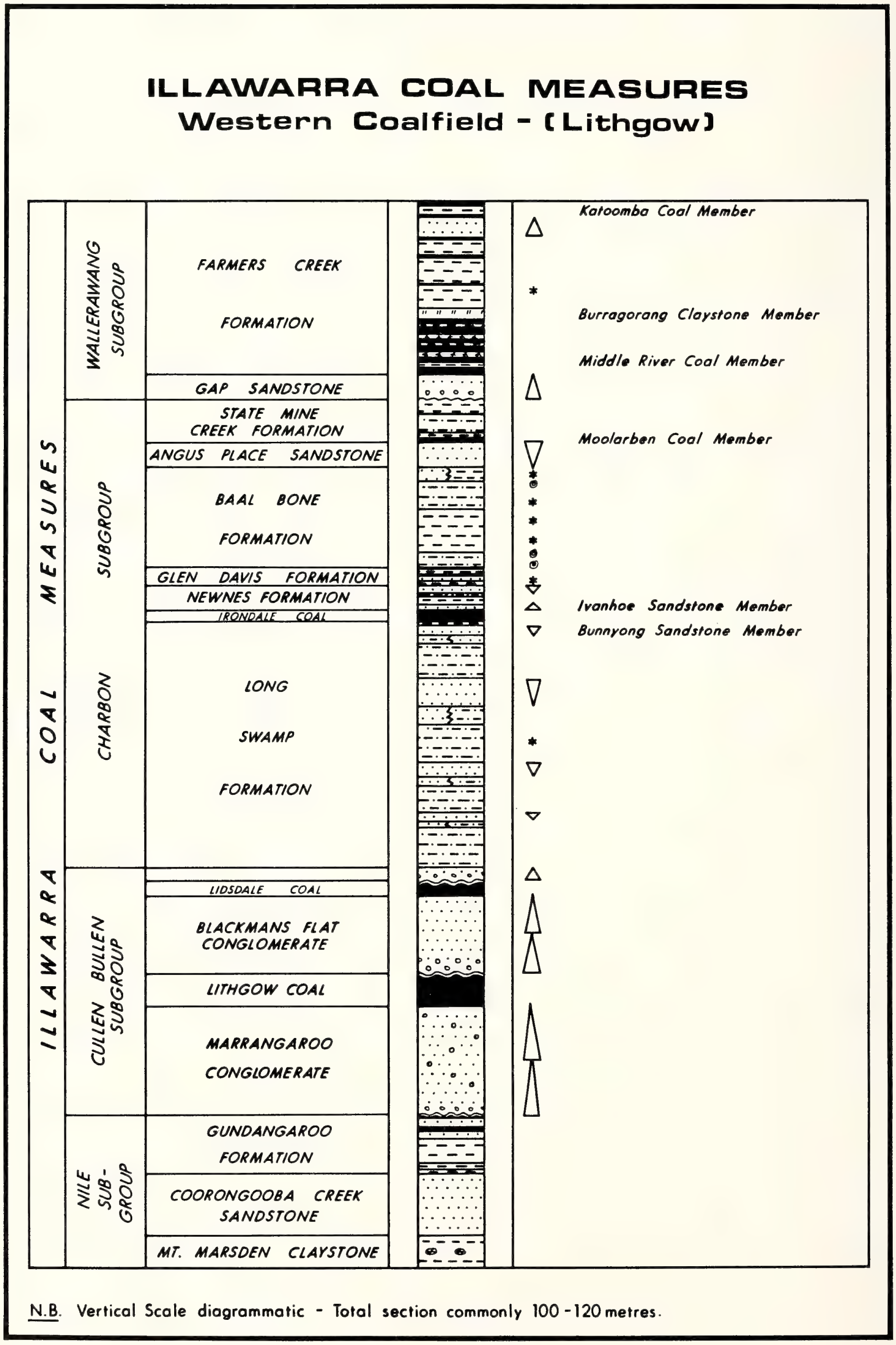
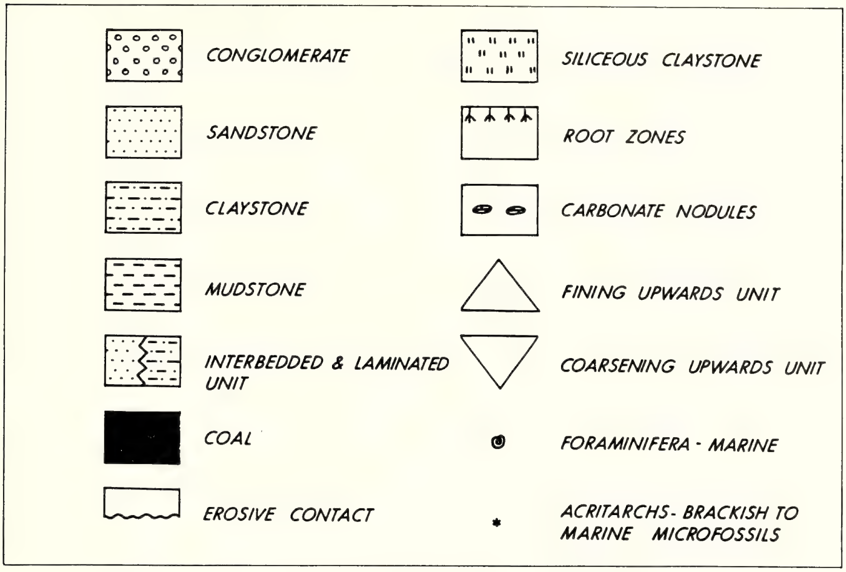


Fig. 2. Generalised stratigraphic column for the Illawarra Coal Measures in the Lithgow district of the Western Coalfield



LITHOLOGICAL KEY - for figure 2

grained quartz-lithic coarsening upwards sandstone units. These latter are commonly overlain by coal. The argillaceous sediments contain acritarchs (microfossils believed to be characteristic of brackish and marine sedimentation) and also, in the Baal Bone Formation only, arenaceous foraminifera. These sediments also have significantly higher boron contents than the underlying and overlying subgroups.

The sediments of the Charbon Subgroup are interpreted as the deposits of pro-delta and interdistributary bay environments, with associated distributary mouth bar and crevasse splay sands. Two major coarsening-upward cycles of lower deltaic sedimentation are represented in this subgroup - the lower one by the Long Swamp Formation and the Bunnyong Sandstone Member, and the upper one by the Baal Bone Formation and the Angus Place Sandstone. Because of its more widespread nature, more abundant acritarchs and presence of foraminifera, a more marine open bay environment is interpreted for the Baal Bone Formation than for the Long Swamp Formation. The Baal Bone lithofacies has also been recognised in the Singleton Area (Denman Formation), the Newcastle area (Dempsey Formation), the Illawarra area (Bargo Claystone) and in the Ulan district. Palynological evidence suggest that a widespread marine depositional episode may be largely synchronous over this area (McMinn, 1981) and a major eustatic change is likely to have taken place at that time.

The presence of arenaceous foraminifera suggests a cold water environment, while the relative abundance of isolated clasts (interpreted as "dropstones"), clast clusters and layers suggests that ice-rafting may have played a part in sedimentation within these bays and interdistributary areas. A climate cold enough to allow river ice to form and be flushed through the deltas to melt in the adjacent bays is envisaged.

It is worthy of note here that the two major coarsening-up cycles of lower deltaic sedimentation (the Long Swamp and Baal Bone cycles) are each capped by relatively thin, but persistent and areally extensive coal horizons (the Irondale Coal and Moolarben Coal Member respectively). This is believed to indicate periods of relative stability in the deltaic sedimentation process.

Wallerawang Subgroup

The depositional sequence of the Illawarra Coal Measures is completed by the Wallerawang Subgroup. This unit represents essentially an upper deltaic to fluvial depositional environment, and is characterised by many thin coals which split and merge, in places forming locally very thick banded coal units. Near the top of the sequence a brief return to lower deltaic bay-fill sedimentation is indicated by a thin siltstone unit in which acritarchs are common (McMinn, 1980).

The sandstones in this part of the sequence are medium to coarse grained, sporadically pebbly and fine upwards. Medium to high angle crossbedding in these beds indicates a relatively high energy fluvial regime and a point bar depositional environment is indicated.

On a coalfield-wide basis, the boundary between the Wallerawang Subgroup and the Narrabeen Group is unconformable. On the Western Margin, the base of the Narrabeen Group is only a short distance

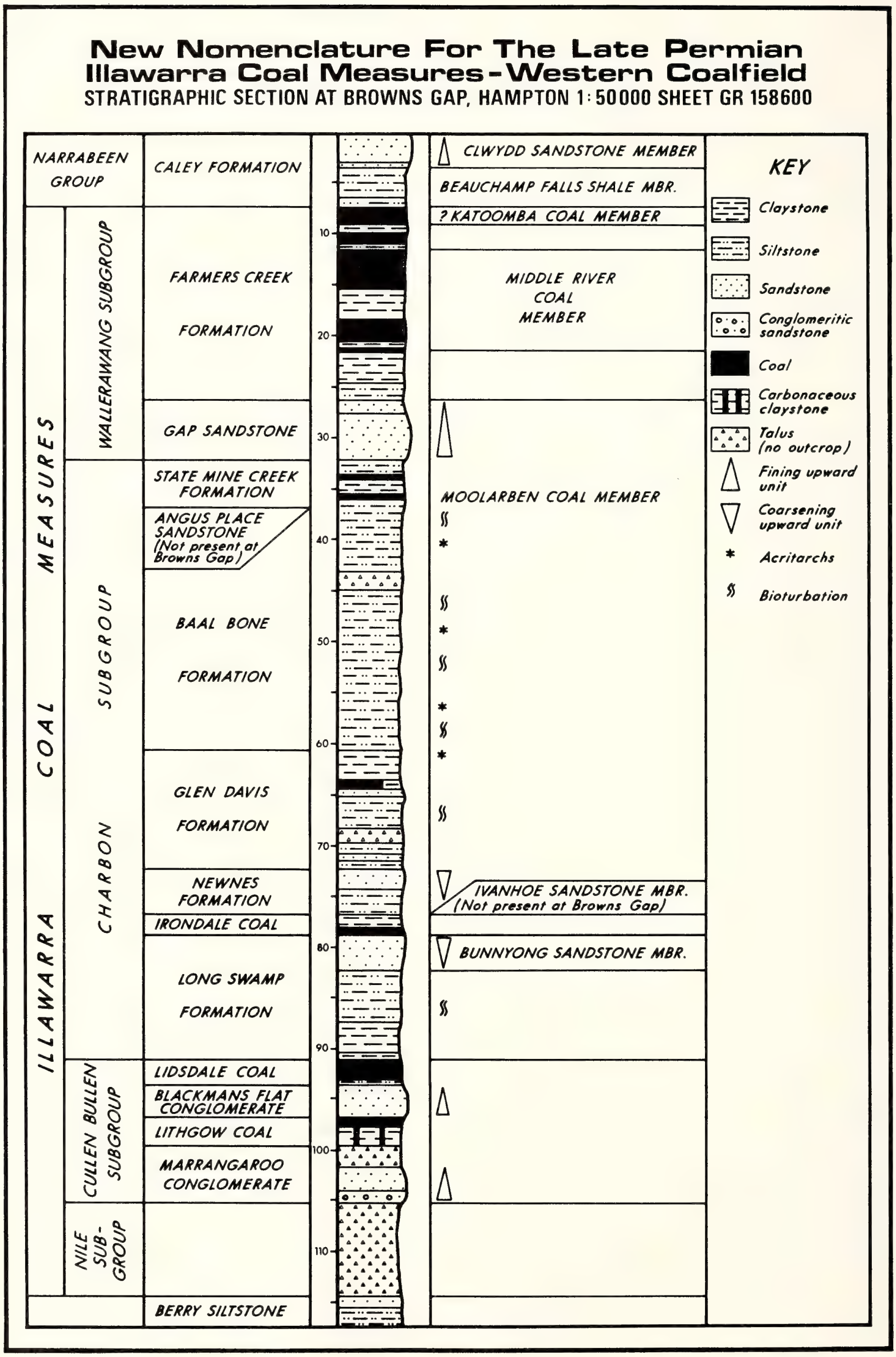


Fig. 3. Stratigraphic section at Browns Gap illustrating the new nomenclature for the Illawarra Coal Measures in the Western Coalfield. (Scale in metres)

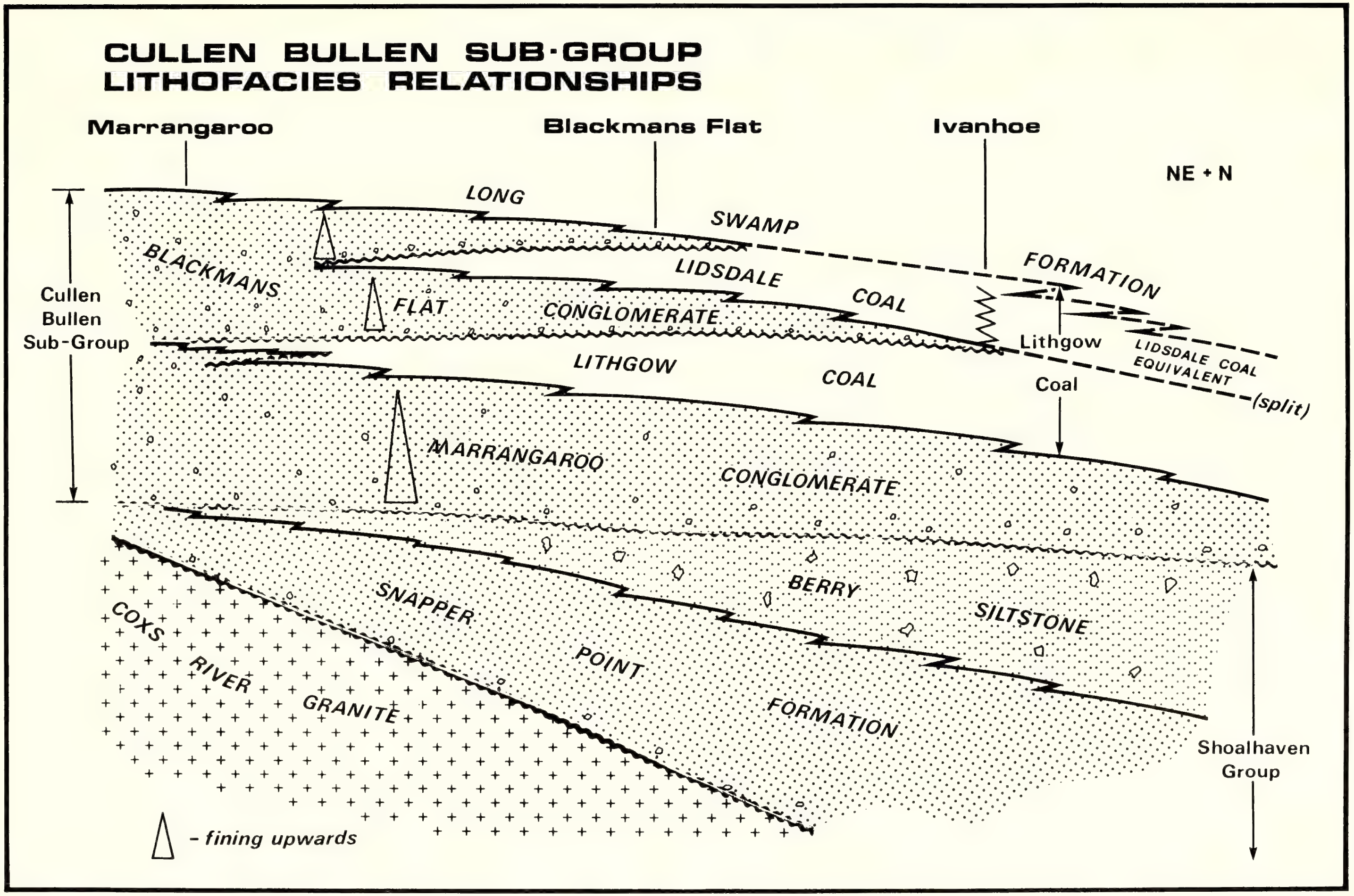


Fig. 4. Diagrammatic lithofacies relationships within the Cullen Bullen Subgroup and Shoalhaven Group near the western margin of the Sydney Basin.

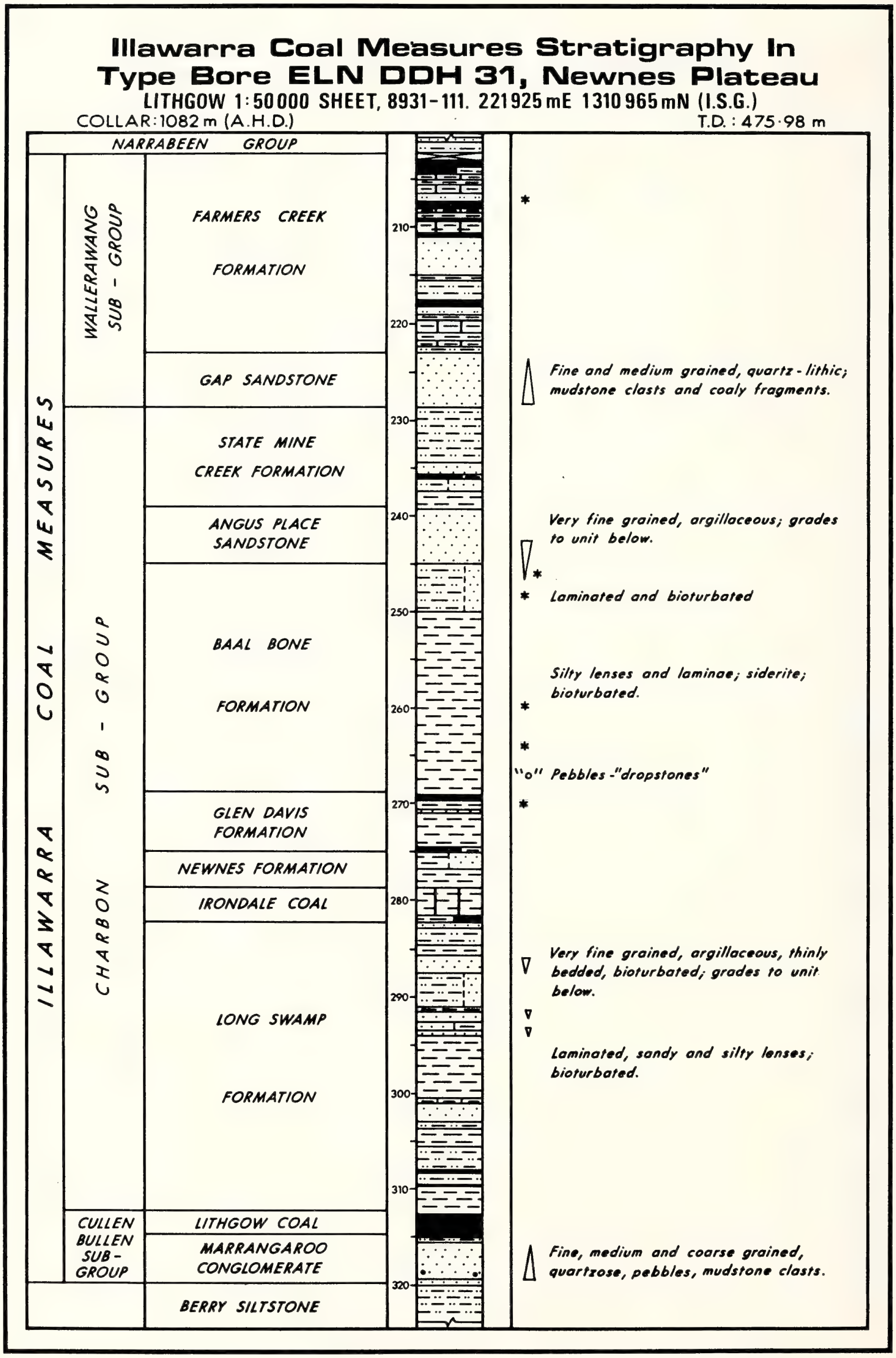


Fig. 5. Illawarra Coal Measures stratigraphy as illustrated in the type bore ELN DDH 31 on the Newnes Plateau, north of Lithgow. (Scale is in metres)

above what is generally called the "Middle River Coal" (e.g. at Browns Gap - see Figure 3). In the Ulan area the equivalent seam is actually truncated by the Narrabeen Group (Shiels and Kirby, 1977), and field mapping (Bembrick, 1979b) indicates that conglomerate-filled washouts occur even lower in the coal-bearing sequence. This relationship is displayed in the Cumbo Creek area, 16 km southeast of Ulan where Narrabeen Group conglomerates are erosive into equivalents of the State Mine Creek Formation. To the east and northeast, in a basinward direction, more and more thin coals appear above the top of the Middle River Coal and some coaly sediments may even occur above the "Katoomba Coal Member".

The relationship between structure and sedimentation is apparent in both the Nile Subgroup (Bembrick and Holmes, 1972) and the Wallerawang Subgroup. The latter has apparently been affected by the northerly continuation of the Mt. Tomah monocline. As that structure is crossed the Farmers Creek Formation thickens considerably with the addition of thicker fine grained clastic units between the thin coals. Much of this clastic material appears to be possibly tuffaceous in origin.

CONCLUSION

A workable stratigraphic subdivision for the Illawarra Coal Measures in the Western Coalfield has been identified and presented. This has enabled correlations and similarities in sedimentation with other areas to be made more readily apparent.

Basically, the Western Coalfield presents a sequence of shoaling lower deltaic sedimentation with relatively minor fluvial channel conglomerates developed near the base. Thick, fine grained, laminated, acritarch-bearing units which are interpreted as interdistributary bay and pro-delta sediments dominate the redefined Charbon Subgroup, which makes up the bulk of the sequence in the Western Coalfield. Arenacous foraminifera are present in the Baal Bone Formation and a cold water marine bay environment of deposition is suggested for this part of the succession.

ACKNOWLEDGEMENTS

An investigation such as this would not be possible without the willing co-operation and support of many mining companies and government organisations. In this regard, I must extend my thanks to Coalex Pty. Ltd., Austen and Butta Ltd., British Petroleum Co. of Australia (incl. Clutha Development Ltd.), Blue Circle Southern Cement Ltd. and the N.S.W. Electricity Commission for providing basic geological data. Thanks are also due to personal from various firms connected with the mining industry, including McElroy Bryan and Associates, Laurie, Montomerie and Pettit, Peter Stitt and Associates.

Special thanks must go to the Coal Section of the N.S.W. Geological Survey (now the Coal Strategy Division of the Department of Mineral Resources) and the Sydney Office of the Joint Coal Board for putting up with my endless enquiries and requests for data.

Much of this work was carried out while on 12 months study leave from Robertson Research (Australia) Pty. Ltd. and was undertaken while studying for an M. App. Sc. Thesis at the N.S.W. Institute of Technology.

The proposed sub-division has been tested by Coalex Pty. Ltd. in geological studies in several parts of the Western Coalfield (C.R. Ward, pers. comm.) and found to be highly successful in evaluation of borehole data for the area.

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(Manuscript received 28.3.1983)
(Manuscript received in final form 26.10.1983)

Journal and Proceedings, Royal Society of New South Wales, Vol. 116, pp. 119-121, 1983
ISSN 0035-9173/83/020119 — 03 $4.00/1

Lambdarina (Rhynchonellacea) from the Upper Visean of Queensland

RODERICK NAZER

ABSTRACT. *Lambdarina granti* sp. nov. is described from the Upper Visean Killala Creek Limestone of the Yarrol Shelf near Mundubbera, southeastern Queensland. It is the first cardiarinid brachiopod described from Australia.

Although sediments of late Visean to earliest Namurian age are relatively common in the Carboniferous succession of eastern Australia, the Killala Creek Limestone is one of the few carbonate units of this age. This being so, it is not surprising that it should yield a somewhat different fauna from contemporaneous clastic formations. Of particular interest are the abundant articulated specimens of *Lambdarina granti* sp. nov. which have been obtained from acid residues of bioclastic limestone from several horizons in the upper 100 m of the formation.

The Killala Creek Limestone is the uppermost unit of the Caswell Creek Group in the Mundubbera district (Whitaker *et al.*, 1974) and belongs to the *Marginirugus barringtonensis* Zone of the eastern Australian biostratigraphic scheme. The late Visean to earliest Namurian age of this zone is well established by conodont, ammonoid and brachiopod studies (Campbell & McKellar, 1969; Jones *et al.*, 1973; Roberts, 1975; Roberts *et al.*, 1976).

Lambdarina granti is noteworthy not only for its small size and unusual morphology but also as it is the first reported cardiarinid brachiopod outside the United States and Britain. *Lambdarina manifoldensis* Brunton and Champion, 1974, from the Lower Visean strata of north Staffordshire, is very similar to the Australian species. This adds to the faunal similarities in Visean times between eastern Australia and western Europe, similarities which Roberts (1981) points out lasted longer in Queensland than in New South Wales. *Cardiarina cordata* Cooper, 1956, from the Pennsylvanian Magdalena Formation of New Mexico, is also similar to the present species. Thus the presence, in the Killala Creek Limestone, of *Lambdarina*, together with *Dorsoscyphus* and *Marginirugus* (Nazer, 1977) points to stronger faunal ties with the American Cordillera in the late Visean than were previously suspected.

SYSTEMATIC PALAEONTOLOGY

Superfamily Rhynchonellacea Gray 1848

Family Cardiarinidae Cooper 1956

Remarks

In size and morphology *Lambdarina* is very similar to *Cardiarina* Cooper, 1956, yet it is excluded from the Cardiarinidae as defined by McLaren (1965, p. H592) as it lacks 'an elaborate parathyridium'. However, although there is no external development of such a structure in *Lambdarina*, the brachial interior requires only little modification to form one. Moreover, as these features sometimes appear in other families, e.g. in *Uncites* (Rudwick, 1974) and *Amphipella* (Cooper & Grant, 1976, p. 1948; where these authors call the structures 'apricatria'), they are not reliable as a basis for family classification. Therefore the definition of the family should exclude reference to the parathyridium and emphasis should be given to the long beak, double sinus and well-developed symphytium, as implied but not stated by Brunton & Champion, 1974.

LAMBDARINA Brunton & Champion 1974

Type Species: *Lambdarina manifoldensis* Brunton & Champion, 1974

LAMBDARINA GRANTI sp. nov.

Derivation of Name

This species is named in honour of Dr. R.E. Grant of the Smithsonian Institution.

Material

ANU 35681 (holotype); ANU 35682 through ANU 35685/20 (23 paratypes). All type material is housed in the Geology Department, Australian National University.

Location

The location is registered with the Department of Geology and Mineralogy, University of Queensland, as L3944 and lies on the eastern flank of a small hill approximately 1.5 km north of Mr. W. Wengel's homestead and 2.5 km northwest of Mundubbera (Nazer, 1977); GR 431822 Mundubbera 1:250,000 Sheet SG 56-5, Queensland.

Description

Minute, heart-shaped biconvex shell with rectimarginate or sulcate commissure. Shell surface smooth; shell substance impunctate. Pedicle valve beak elongated, perforated apically by round foramen; symphytium flat to slightly arched. Deep sulcus developed on anterior half or two-thirds of valve, frequently with low median fold (Fig. 1, F). Valve moderately convex, with indented anterior margin corresponding to sulcus. Thin dental

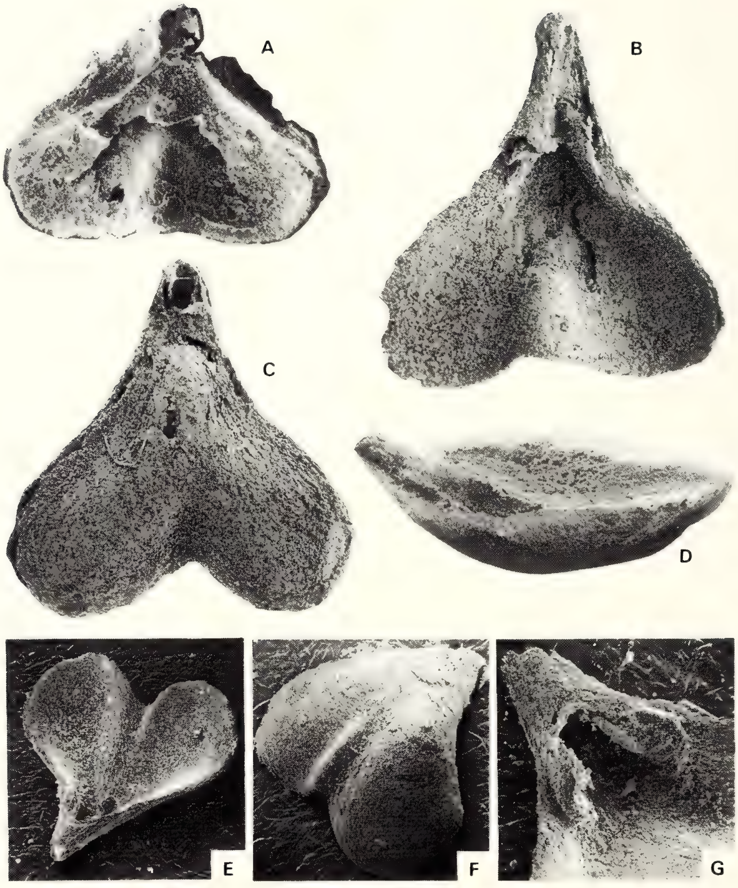

Fig. 1. *Lambdarina granti* sp. nov. A, Internal view of brachial valve, X25, ANU 35682. B, Internal view of brachial valve with portion of pedicle beak attached, X28, ANU 35683. C, Dorsal view of articulated specimen (holotype), X28, ANU 35681. D, Lateral view of articulated specimen, X28, ANU 35684. E, Oblique internal view of pedicle valve, X18, ANU 35685/1. F, Oblique external view of pedicle valve showing median fold in sulcus, X18, ANU 35685/2. G, Oblique internal view of pedicle valve showing symphytium and dentition, X50, ANU 35685/1.

plates, partly or completely fused to sides of valve, extending from umbonal region as far as teeth, which longitudinally elongate and concave inwards (Fig. 1, E,G), remainder of valve interior smooth.

Brachial valve moderately convex with weakly developed umbo; sulcus developed in anterior half producing indented anterior margin. Brachial interior with inner socket ridges integrated with cardinal process and extending antero-laterally to meet valve margin at half the valve length; small cavity beneath anterior end of cardinal process (Fig. 1, A,B); remainder of valve interior smooth.

Measurements

	Length	Width
ANU 35681 (holotype)	2.5 mm	2.4 mm
ANU 35685/4	2.1	1.8
ANU 35685/5	2.3	2.4
ANU 35685/6	2.4	2.4
ANU 35685/7	2.8	2.7

Discussion

Outer socket ridges appear to be absent in this species, the teeth being inserted between the described socket ridges and the valve wall. Articulation is assisted by the curvature of the teeth. The depressed areas in the illustrated brachial interiors (Fig. 1, A,B) are interpreted as preservational features.

Lambdarina granti is very similar to the type species *L. manifoldensis*. Indeed, it would be difficult to separate these two species if they occurred in the same geographic area. The main differences appear to be the better developed socket ridges in the brachial valve of the Australian species, its slightly larger size and broader lobes.

The intermittent recovery from acid residues of numerous specimens of *Lambdarina granti* suggests that the species lived in clusters, attached by a functional pedicle throughout life, in the relatively quiet water carbonate environment (Nazer, 1977).

ACKNOWLEDGEMENTS

Scanning electron micrographs were taken by the S.E.M. Departments of the University of Queensland and the Australian National University. The author is grateful for assistance received from Dr. K.S.W. Campbell and Dr. P.A. Jell.

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(Manuscript received 28.9.1983)

Journal and Proceedings, Royal Society of New South Wales, Vol. 116, pp. 123-127, 1983
ISSN 0035-9173/83/020123 — 05 $4.00/1

Dextral Movement on the Demon Fault, Northeastern New South Wales: A Reassessment

J. McPhie and C. L. Fergusson

ABSTRACT. The Demon Fault is a meridional transcurrent fault extending for at least 200 km in the eastern part of the New England Orogen. The southern margin of the Late Permian Coombadjha Volcanic Complex, and contacts between units within it, are displaced for 23 km in a dextral sense along the Fault. In the Cooraldooral Creek area the Fault consists of at least four major fractures. This contrasts with the Timburra River area where the trace of the Fault is marked by an elongate zone of sheared rock 500 m wide.

INTRODUCTION

The Demon Fault (or Fault System) was recognzed by Shaw (1969) to be a major transcurrent fault in the New England Orogen of northeastern New South Wales (Fig. 1). The Fault extends from Ebor in the south for 200 km following a northward meridional trend. Shaw (1969) estimated dextral strike-slip movement amounting to about 30 km on the basis of the displacement of the Stanthorpe Adamellite.

Korsch *et al.* (1978) documented the general characteristics of the Demon Fault and described its effects in detail for two sites. They rejected Shaw's estimate in favour of offset amounting to only 17 km. This figure was arrived at by matching the contact between the Dundee Rhyodacite and the Bungulla Porphyritic Adamellite on either side of the Fault in the Timbarra River area (their Fig. 3, 1978).

Further fieldwork in the Timbarra River area, herein reported, indicates 23 km of dextral movement on the Demon Fault since the time of emplacement of the Early Triassic Dandahra Creek Granite. Details of the character of the Fault in this area and at one other locality (Cooraldooral Creek) are also described.

DISPLACEMENT OF THE COOMBADJHA VOLCANIC COMPLEX

The Coombadjha Volcanic Complex is comprised of Late Permian terrestrial silicic volcanics and related granitoids preserved adjacent and to the east of the Demon Fault in the upper reaches of Coombadjha and Washpool Creeks (Fig. 2). The Complex has a mappable internal stratigraphy and structure which suggest that it is the eroded remnant of a volcanic cauldron (McPhie, 1982). Only those features relevant to the Demon Fault movement are described here.

Volcanic and plutonic rocks of the Complex along its southwestern margin are intruded by the Dandahra Creek Granite, and all these rock units are truncated by the Demon Fault. Three of the five informal volcanic units of the Coombadjha Volcanic Complex can be traced to the Fault. The two older units (Units A and C of McPhie, 1982) are both outflow sheets of welded ignimbrite. In the field these units are distinguishable from each other on the basis of the mineralogy and proportion of crystal fragments, and on the character of the pumice lenticle foliation. The youngest unit is a representative of the Dundee Rhyodacite, a widespread and distinctive crystal-rich ignimbrite characterised by tor-like outcrops and textures similar to those of porphyritic granitoids. These three volcanic units are dipping to the north or northwest at shallow angles ($10-25^0$). The contact with the Dandahra Creek Granite is sharp, and dipping steeply to the north.

These same three volcanic units and the Dandahra Creek Granite have been located to the north on the west side of the Demon Fault (Fig. 2). Contacts between the volcanic units, and between the volcanics and the Dandahra Creek Granite on the east side of the Fault are consistently offset for 23 km in a dextral sense to the Boundary Creek area. The quality of the outcrop in this area west of the Fault is poorer, particularly within the Dundee Rhyodacite. Further west, the Complex is intruded by the Billyrimba Leucoadamellite. To the north in the Demon Creek area, the Dundee Rhyodacite outcrops in isolated patches surrounded by microgranite forming the shallow east-dipping roof zone of the Bungulla Porphyritic Adamellite. No single straight-line contact exists in this area between the Dundee Rhyodacite and the Bungulla Porphyritic Adamellite (*cf.* Korsch *et al.*, 1978, Fig. 3).

THE DEMON FAULT IN THE TIMBARRA RIVER AREA

Here the Demon Fault separates the Coombadjha Volcanic Complex to the east from undifferentiated complexly deformed Palaeozoic sedimentary rocks to the west (Fig. 3). One main fracture is present, marked by poor exposure. For 500 m to the west of this fracture, the deformed Palaeozoic rocks are pervasively sheared with many randomly oriented shear surfaces and complete destruction of sedimentary layering. The volcanics on the east side within 50 m of the fracture are closely jointed.

The complexly deformed rocks on the west consist of argillite, argillite-tuff, massive tuffaceous(?) rock, thin-bedded turbidite and massive greywacke. Bedding in much of this sequence is near vertical and striking northwest. Sparse exposures of graded bedding and micro-cross-

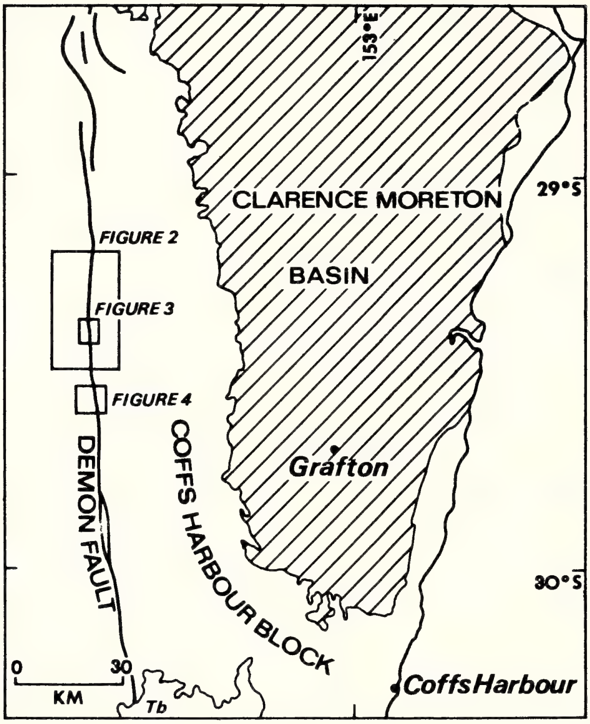

Fig. 1. Locality map, northeastern New South Wales
Tb - Tertiary basalt.

lamination indicate northeasterly younging directions. Slaty cleavage is sporadically developed in argillite.

THE DEMON FAULT IN THE COORALDOORAL CREEK AREA

There are two major arms of the Demon Fault in the Cooraldooral Creek area (Fig. 4), each marked by prominent air photolineaments. These fault branches are entirely within complexly deformed sedimentary rocks. Two informal units of the Coffs Harbour beds occur east of the fault (Fig. 4): a northeastern unit (Chb_2) of argillite and less abundant thin-bedded turbidite and massive greywacke, and a southwestern unit (Chb_1) of thin-bedded turbidite and massive greywacke in similar proportions. To the west of the fault the sequence is dominated by argillite with less abundant thin-bedded turbidite, massive greywacke and intermediate volcanics. Areas of sheared rocks are exposed in Barool Creek 1 km west of the fault. Bedding on both sides of the fault is steeply dipping and northwesterly striking, with most younging directions facing towards the northeast. In the Coffs Harbour beds there are at least two tight to isoclinal fold pairs, with west-younging limbs up to 500 m across, and sporadically developed slaty cleavage in argillites.

Two additional fractures to the west of the main arms of the fault offset an east-west trending, vertical, quartz-feldspar porphyry dyke (Fig. 4). The dyke is up to 100 m thick and forms a cliffline, the displacement of which is easily seen on air photos.

CONCLUSIONS

Detailed mapping of silicic volcanics either side of the Demon Fault has revealed 23 km of dextral strike-slip movement. The relationships herein described support Shaw's (1969) conclusion that this movement occurred after the cessation of Permo-Triassic silicic volcanic and intrusive activity within the region. Prior existence of the Fault is unlikely, since there is no evidence of its influence on either the original stratigraphy or primary structure of the Coombadjha Volcanic Complex.

Study of the tectono-stratigrphic units of the Coffs Harbour Block has enabled correlation of this area with the Texas-Warwick area (Fergusson, 1982; Flood and Fergusson, 1982). Extrapolation of boundaries of the equivalent tectono-stratigraphic units of each of these areas gives a result consistent with the 23 km of movement indicated from this study of the Fault.

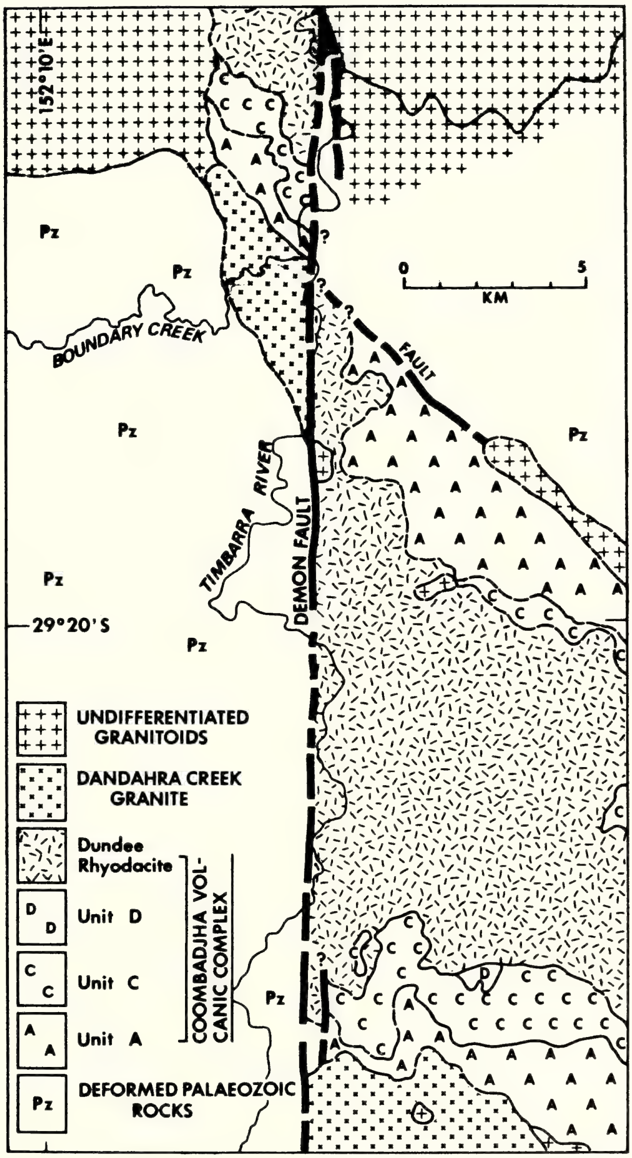

Fig. 2. The geology of the Timbarra River area showing the 23 km of dextral displacement of the Coombadjha Volcanic Complex along the Demon Fault.

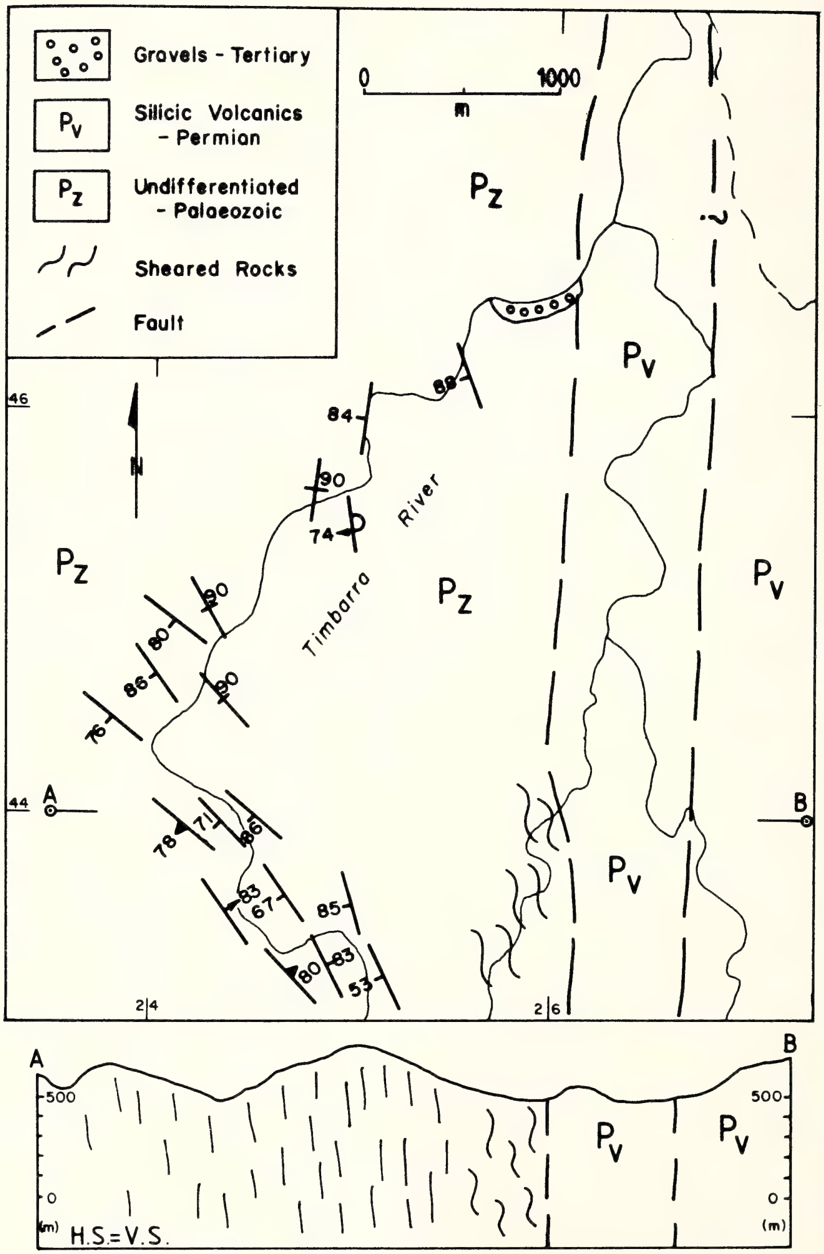

Fig. 3. Detailed map of the Demon Fault along the Timburra River. See Fig. 4 for a key to structural symbols.

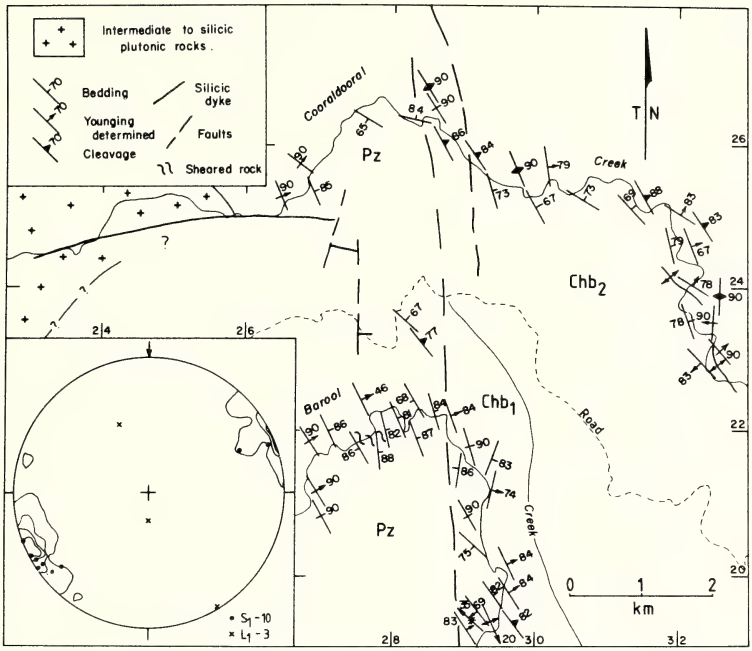

Fig. 4. Detailed map of the Demon Fault in the Cooraldooral Creek area.
P_z - undifferentiated Palaeozoic sedimentary rocks.
Chb_1 and Chb_2 - subunits of the Coffs Harbour beds.
Equal-area stereogram, 58 bedding poles contoured at 5-10-15-20% per 1% area.

ACKNOWLEDGEMENTS

We thank Peter Flood for helpful discussions and his review of the manuscript. Rhonda Vivian kindly typed the draft.

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(Manuscript received 11.7.1983)
(Manuscript received in final form 26.10.1983)

Journal and Proceedings, Royal Society of New South Wales, Vol. 116, pp. 129-140, 1983
ISSN 0035-9173/83/020129 — 12 $4.00/1

The Teaching Hospital: Past, Present and Future

JOHN B. HICKIE*

ABSTRACT. Teaching hospitals have recently been under attack in Australia, Great Britain and the United States (Rogers & Blendon, 1978; Westerman, 1980). Much criticism arises from a lack of knowledge and understanding of the origin, history and multiple functions of these institutions.

HISTORICAL REVIEW

Europe

During medieval times medicine in Europe developed mainly in the Universities. From the middle of the 13th century students gathered around teachers from the monastery schools at Oxford and Cambridge and were given occasional theoretical lectures. They were then apprenticed to private practitioners or came to London for unorganised clinical teaching. As a result teaching in medicine in England developed outside the universities primarily in hospitals. Addenbrookes Hospital, Cambridge, was founded in 1766. There were difficulties with funds and there were too many students for the size of the hospital, a situation not dissimilar to that in some of our teaching hosptials today (Poynter, 1966).

The first teaching hospital was probably at the University of Padua in the 15th century, where della Monte (1489-1552) began bedside teaching at the hospital of St. Francis in Padua.

The first effective clinical teaching occurred about 1636 at Leyden when in turn Franciscus Sylvius and later Hermann Boerhaave attracted local and foreign students. Although Boerhaaave gave instructions on patients in only 12 beds, he had a major influence on the foundation of the Edinburgh School of Medicine with its strong clinical component (Singer & Underwood, 1962).

Scotland never possessed a medieval school of medicine such as Oxford or Cambridge. The Scottish Universities especially Edinburgh, established in the 15th and 16th centuries, developed strong anatomical and clinical traditions within their Royal infirmaries which were established in the 18th century. They were particularly influenced by clinical teaching at Leyden and they in turn had a large influence on the hospital and medical school traditions of both Australia and the United States.

Students from Oxford and Cambridge who came to London as well as the need to train apothecaries and surgeon-barbers lead to the development, between 1746 and 1914, of private medical schools in London. Students also individually attended St Bartholomew's Hospital from 1662 (Paynter, 1966) and St. Thomas' Hospital included in its hospital standing orders in 1699 that "no skillet carriers (students) are allowed except at the surgeons charge" (Graves, 1947). The London Hospital Medical College was founded in 1785 to be a complete medical school within a hospital (Poynter, 1966). During the first part of the 18th century, as the population of London increased, the rich became increasingly aware of the sick poor. St. Bartholomews and St. Thomas' Hospitals were rebuilt, the Westminster, St. George, Mr. Guys, the London and the Middlesex Hospitals were founded. They were run by laymen boards with a few philantrophically minded medical men among them. Although there was much genuine philanthropy, the interests of many were not entirely altruistic. Being on the board might help one climb the social ladder and being an honorary was a hall mark of medical success. As the teaching hospitals developed they provided more practical experience and the"private medical schools" in London slowly faded out. The first whole-time academic unit for teaching and research in England was established at University College Hospital under Sir Thomas Lewis in 1915 (Miller, 1969). Up until the Haldane Commission in medical education in London in 1913, medical education was dominated by the hospitals. The universities had a more dominant role in the provinces and in Scotland. Following the Haldane Commission, and submissions by Abraham Flexner, the conceipt of University support and influence in teaching hospitals was accepted.

In continental Europe two different kinds of medical school developed. In France particularly Paris the clinical-hospital school with outstanding teachers and the "demonstration of hundreds of cases each year in ward rounds or in special clinics" (Singer & Underwood, 1962) attracted students.

In Germany, Austria, Holland, Scandanavia and parts of Switzerland, from 1850 to 1900 there was much greater emphasis on research. The clinical professor's clinic in hospital was a university department. The professor was expected to be a medical scientist rather than a well known practitioner. The hospitals used by medical schools came to be dominated by professorial departments.

* Based on a Lecture delivered before the Royal Society of New South Wales on 6th October, 1982.

America

The first medical school in the new world was founded in Philadelphia in 1765 at the College of Philadelphia. The College trustees invited Dr. John Morgan who had earned the M.D. degree at the University of Edinburgh to give the commencement address. He laid down guide lines for the development of medicine as a university discipline including "hospital instruction should form an integral part of instruction in medical school and teachers should have time to experiment and search for the secrets of nature" (Norwood, 1965). The McGill Medical School in Montreal founded by Scotsmen, had from its conception closely followed the educational methods in vogue at Edinburgh. Osler stated "when I began clinical work in 1870 the Montreal General Hospital was an old coccus - and rat ridden building, but with two valuable assets for the students - much acute disease and a group of keen teachers" (Cushing, 1925). When the Johns Hopkins Medical School was founded in 1909, it was in the Edinburgh and German tradition with a close affiliation between the medical school and university. This was in contrast to most other American medical schools which were mainly privately run money-making institutions with poor standards. This situation was revolutionized by the Flexner Report in 1912.

Following this report two types of teaching hospitals developed. One, the hospital "closely integrated physically, administratively and financially with the medical school with which it shares common objectives...." and two, "The affiliated hospital that functions as a separate institution but grants privileges to a variable degree to the medical school ...." (Shryrock, 1965). Many of the former developed into the "University Medical Centre" (Rogers & Blendon, 1978), a joint effort of the health services, the medical school and the university with private funding an important part of the cost structure. Probably because of Flexner, Johns Hopkins and American visits to Europe for postgraduate study, the German-American pyramidal system of academic control of medical staff and research, evolved (Shryrock, 1965). There are now 120 academic medical centres in the United States and 61 of them are centres in the centre of the 40 largest cities. The American teaching hospitals have influenced Australian medicine in the last 10 - 15 years, especially in the development of specialisation and clinical research.

Australia

Many of the traditions of Australian medical schools and Australian teaching hospitals arose initially from doctors and nurses who trained in teaching hospitals in Britain and Europe. These and local graduates were influenced by visits to Britain and Europe and in the years following the Second World War by visits to the United States. It is relevant that British and American hospitals now have similar problems to Australian teaching hospitals re site, funding referral patterns, community obligations, specialisation and administration.

Australian teaching hospitals were established as benevolent institutions developed by individuals who were concerned with providing medical care for the "sick poor" and hospital facilities for their medical staffs. Melbourne University Medical School began in 1862. The rules of the hospital for 1863 had already provided that "pupils to the medical and surgical practice of the hosptial will be admitted after payment of fees to be arranged by the medical officers with approval of the Board"(Inglis, 1958). The first clinical school began in 1864 but the hospital did not become an offical teaching hospital until 1888. Dr. A.C. Brownless who was a member of the University Council and an Honorary Physician to the Hospital "hoped that medicine at Melbourne would be taught not as it was taught at either Oxford or Cambridge or in the English Hospitals; he hoped to reproduce that harmony of theory in practice, at the university and hospital, which he had found in Europe - and in Scotland, in which in education as in other affairs it was more sensitive than England to winds that blew from the Continent. But the Melbourne Hospital, to Brownless' disappointment was in no way attached directly to the University. It was a mile away and run by men who were no more prepared to be dominated by the university than was the university council ready to let its affairs be managed by the hospital. It was not until 1910 that the hospital and the university was able to establish a satisfactory arrangement for the training of doctors" (Inglis, 1958). This was in the London tradition.

The Alfred Hospital was opened in 1871 south of the Yarra. One of its objectives was to improve the opportunities for students, yet no constitutional provision was made for students, in fact the students protested at the standard of the teaching. The hospital was an even greater distance from the university campus and initially the staff were hostile to both students and the university. The standard of medical care was poor, and the hospital was known as "The Butcher Shop" in 1876. It was however, the first hospital in Australia to allow female medical students and residents. In 1926, the Baker Medical Research Institute was opened as a pathology and biochemistry department. "The presence of modern laboratories and specialised staff stimulated the flow of clinical work from the hospital wards. Within a year research scientists at the Baker Institute were complaining that too much of their time was absorbed by routine work for the hospital. Thomas Baker exercised his option and oblighed the hospital to contribute towards Institute costs. This move was resented by members of the hospital board and the crisis which precipitated it, namely the conflict between research aims and routine needs damaged relations between the two institutions until 1949" (Mitchell, 1977).

The Sydney University Medical School did not begin until 1883. "In 1868 during the visit of H.R.H. Prince Alfred to Sydney, he was shot and seriously wounded; upon his recovery as an expression of public thankfulness, it was decided to raise a fund to be appropriated to the provision of a suitable memorial. It was decided that this should take the form of a hospital, to be known as the Prince Alfred Memorial Hospital.

A controversy arose as to how and where the proposed hospital should be erected. A proposal that it should take the form of a new front to the

old Sydney Infirmary came to nothing. Finally, some wise person saw an opening for the erection of a hospital on the area known originally as "Grose Farm"....By arrangement between the Committee for the Memorial Fund and the Senate of the University an Act was passed in 1873 to provide for the foundation of the hospital.... the Act stipulated that the medical staff of the hospital should be appointed by a Conjoint Board.... and that students of the medical school (still proposed) should be allowed to attend the hospital for clinical teaching" (Epps, 1922). Anderson Stuart became Professor of Anatomy and Physiology in the University of Sydney in 1882 and the medical school began with his arrival in Sydney in 1883. He was also Dean of the Medical School, a member of the Board of Directors of the Royal Prince Alfred Hospital from 1883 till 1920, and its Chairman from 1901.

His position highlights one of the differences in the teaching hospitals of Melbourne and Sydney. The former were developed in the London tradition and still have clinical titles similar to London. The Sydney scene and especially the Royal Prince Alfred Hospital followed the Edinburgh tradition with much closer university involvement. "The hospital was funded as a University hospital built on University grounds.... the relations with the University have always been harmonious as they should be between great public institutions so closely interrelated in their work and objects" (Schlink, 1933). Despite the university traditions there were no full time professors in clinical disciplines until the appointment of the first full clinical professors in Australia, Professor H.R. Dew, as Professor of Surgery, and Professor C.G. Lambie, as Professor of Medicine in 1930. It was not till the 50's that full time professors were appointed in Adelaide, Brisbane and Melbourne.

Sydney Hospital, the oldest hospital in Australia, probably began on its present site in about 1816. Under the provisions of the Sydney Hospital Act of 1881 medical students were permitted to attend the practice of the hospital, but there was little advantage to them because their attendance was not encouraged by the honorary medical staff many of whom resented their presence. Early in 1909 the Board of Sydney Hospital approached the Senate of the University of Sydney with a view to opening the hospital to medical students. The report of Sydney Hospital of 1909 states "Sydney Hospital should be thrown open to medical students so that medical students should have the choice of attending either Sydney or the Royal Prince Alfred Hospital ---- it must be an advantage to the Royal Prince Alfred Hospital to have the pressure on its resources relieved" (Stokes, 1960). A Board of Medical Studies was appointed on which the hospital seems to have had the major representation. Professor Anderson Stuart at the time of the opening of the Sydney Hospital Clinical School in 1909 said "it was a very good thing for the hospital to come into connection with the medical school of the university because it stimulated work there" (Stokes, 1960).

Mother Berchmans Dalley, the Superior General of the Order of the Sisters of Charity, negotiated in Melbourne in 1909 the affiliation of St. Vincent's Hospital, Melbourne with Melbourne University and in 1923 carried through a similar negotiation with the University of Sydney.

St. Vincent's Hospital, Sydney, the first hospital to have trained nurses in Australia, began in 1857 and took medical students unofficially from 1886. Sir Douglas Miller in narrating the early formation of the clinical school, states "in the forming of the school it was essential that the University should be satisfied with the status of the teaching staff and this required termination of some appointments and the supersession of others. The condition that the University should have a decisive voice in future appointments, necessitated the relinquishment in large measure of the rather cherished function of the sisters to choose their own medical staff. The agreement gave the sisters the right to advertise the appointment and to submit their choice in order of preference to the University Senate" (Miller, 1969). The Hospital Report of 1923 summarises the advantages to the patients of a teaching hospital "lecturers in a clinical school must look to their laurels; nobody there can live on an unearned reputation. They must be ever on the alert, for keen ears are listening, keen eyes watching and keen brains appraising their work. The patients in a teaching hospital are assured of the best attention that doctors can give. Ailments are subjected to the scrutiny first of junior medical officers, who are jealous of their own diagnoses; symptoms are weighed; advice is sought; opinions are tossed from mind to mind ---- the patient may have reassurance that all that is humanly possible has been done" (Miller, 1969).

The University of Adelaide was established in 1874 and was the third Australian university. The Royal Adelaide Hospital developed through "four hospitals" from the beginning as the "Colonial Infirmary" in 1841 (Estcourt Hughes, 1967). It entered the field of medical education in 1887 although the Adelaide Medical School began in 1885 with a five year course which produced its first four graduates in 1889. It is unique in the history of Australian medical education and teaching hospitals. Due to a "hospital row" in 1894, all the honorary medical staff resigned in 1896, teaching was disrupted until 1901 and medical students had to complete their medical course elsewhere.

Some comments in 1967 from J. Estcourt Hughes in his "A History of the Royal Adelaide Hospital" under "The Hospital and Medical Education" are relevent to the changing scene in Australian teaching hospitals in the last thirty years. "When the University of Adelaide decided to appoint professors in the principal clinical subjects, the move was widely, but not unanimously, approved. It was recognised that the world trend in medical education was towards either having university teaching hospitals e.g. hospitals which the universities controlled - with professors in charge of the various departments.... or alternatively, to establish professorial units in teaching hospitals which the university did not control.... the staffs of which would devote their whole time to teaching, research and liaison with other university departments.... There were however, certain reservations.... These were mostly concerned with the questions of how far the professors should be allowed to dominate the hospital scene and to what extent they should be allowed to engage in private practice.... It is to be hoped that the tradition

of teaching commonsense matter in commonsense way will continue" (Estcourt Hughes, 1967).

These were the major teaching hospitals in Australia with the exception of the Royal Brisbane and the University of Queensland (1936) up till the Second World War. In the majority, the clinical teaching was dominated by the honorary medical staff and even those who had university appointments were in private clinical practice. The teaching was concerned with training and was along the hospital dominated medical school traditions of Britain and France, especially London. The students learned by precept and example. The aim was to produce fully trained general practioners. Many of those who were teaching within the hospitals had come in to consultant practice through general practice. "Considering the amount of clinical material dealt with at the hospital.... the staff contribution to the advance in medical knowledge.... had been very small indeed" (Estcourt Hughes, 1967).

Following the Second World War, there was an increase in the number of medical schools in Australia and an explosion in academic departments within teaching hospitals. World wide medicine became more scientific. Rapid developments in technology influenced diagnosis and treatment. Greater emphasis was placed on research, especially clinical research, postgraduate training, continuing education and the development of specialist departments. The staff of the teaching hospitals were increasingly influenced and received postgraduate training within American medical schools. The aim of undergraduate training was to produce graduates who following internship could undergo graduate and postgraduate training.

Today undergraduate medical education is provided in Australia in ten university based medical schools (Rotem, Craig, Cox & Garrick, 1979) (Table 1). There are 24 major teaching hospitals and about 53 associate, special, or affiliated teaching hospitals (Table 2). The major teaching hospitals are also generally large referral hospitals. The use of the term associate, affiliate and special has caused confusion. These latter hospitals are institutions which provide some supplementary teaching and clinical experience for medical students but they do not have academic departments, a large compliment of full time staff, and are not active in clinical research. They have been developed both in Australia and the United States in response to increased enrolments, more training positions and different kinds of experience for students. The title may help hospitals attract better staff but it has confused Health Administrators and complicated University Hospital relationships (Cohen, 1981).

THE MODERN TEACHING HOSPITAL - CHANGES IN RECENT YEARS

In recent years the type of patient treated in a teaching hospital has changed from the "sick poor" to patients from all sections of the community. The concept of the sick poor has to be seen in a broader context. The community requires and expects the sophisticated diagnostic and therapeutic techniques of modern medicine. The district hospital needs to be able to refer complicated medical and surgical problems to major centres. Unfortunately, some health authorities regard the teaching hospital as a tower of high technology, of dubious service value created at enormous expense to meet the needs of teaching and research and providing inadequate facilities to a local population. Others who do not understand the interrelationships of good patient care, teaching and research see referral centres as separate from teaching hospitals.

The teaching hospital as part of the medical school has two functions separate from but interwoven with patient care. There are training on the one hand, education, and the advancement of medicine on the other (Ellis, 1918). Training needs clinical services and examples of current practice and commonly occurring conditions. Education and the advancement of medicine requires a substantial supply of unusual and difficult clinical problems with appropriate technology and scientific back up. The Todd Report on medical education in 1968 stated "A teaching hospital's education functions will require a full range of general and special departments and these must be big enough to provide adequate and economical care, they will often have to be larger than this in order to meet either service needs or the needs of eduction - but they will be limited by the number of patients who need treatment and by the staff and money available. A teaching hospital will always have special facilities which must be available to patients from outside its own district. The local population served by a big single University Hospital should therefore be smaller than that served by an ordinary district hospital the same size" (Ellis, 1918). Todd saw that there could be conflict in teaching hospitals in meeting both the community needs and fulfilling their roles as centres of clinical excellence. It is a matter of priorities and each institution has to decide how to resolve the priorities and minimise the conflicts. The history of all the teaching hospitals in Australia indicates that they have changed over the last 100 years in response to a variety of community needs.

THE CHARACTERISTICS OF AN AUSTRALIAN TEACHING HOSPITAL

Australian teaching hospitals have the following characteristics:

1. Size. They are large. The bed size usually exceeds 400 and some have in excess of 1000 beds (Duckett, Scarf, Schmiede & Weaver, 1981).

2. Complexity. There is a conglomerate of general and highly specialised medical services. In Australia they are all located in large cities especially the State capitals (Duckett, Scarf, Schmiede & Weaver, 1981).

3. Size of the Staff. There is usually a large intern, resident and registrar staff related to the large number of beds, the complexity of the case-mix and post-graduate training.

4. Referral Hospitals. There is a wide range of special units or divisions within the

TABLE 1

MEDICAL SCHOOLS IN AUSTRALIA

Medical School	Year Established	Length of Course	Student Numbers Intake (1977)
University of Melbourne (Vic)	1862	6 years	220
University of Sydney (NSW)	1883	5 years	250
University of Adelaide (SA)	1885	6 years	120
University of Queensland (Qld)	1936	6 years	245
University of Western Aust. (WA)	1957	6 years	120
Monash University (Vic)	1961	6 years	160
University of New South Wales (NSW)	1961	5 years	240
University of Tasmania (Tas)	1965	6 years	48
Flinders University SA)	1974	6 years	64
University of Newcastle (NSW)	1978	5 years	64 (1978)
		TOTAL:	1531

TABLE 2 *

UNIVERSITY TEACHING HOSPITALS

UNIVERSITY	TEACHING HOSPITALS	
	Major	Associate, Special, Affiliated
Sydney	5	16
New South Wales	4	6
Newcastle	2	1
Melbourne	4	7
Monash	2	8
Queensland	3	10
Adelaide	2	?
Western Australia	1	4
Tasmania	1	1
TOTAL	24	53

* Source University Calendars, 1982

subdivisions of medicine and surgery. These provide complicated diagnostic and therapeutic services for patients referred from other hospitals. This function cannot be separated from teaching.

5. Laboratory Facilities. These are wide in both their scope and intensity. They often serve as referral or reference laboratoes for the State.

6. Outpatient and Casualty Departments. These are very large and active.

7. Clinical Research. There is a very active programme of clincial research and an academic department involved in clinical research. There may also be a special research institute. The investigational ethic is basic to the true teaching hospital.

8. University Affiliation. They all have a close link with a university. The staff are integrated with the medical faculty and many of the hospital staff have either clinical teaching appointments or conjoint academic appointments.

9. Full Time Staff. There is a nucleus of full time staff specialists especially in internal medicine. All the ancillary services have full time salaried chiefs of staff.

10. Finance. The financial arrangements within the teaching hospitals are complicated. The hospital usually receives major funding from the State and Commonwealth health services but also receives additional funding from private patient fees, Hospital Contributions Funds, the Universities, private donors and research funding bodies such as the National Health and Medical Research Council.

THE DIFFERENCES BETWEEN A TEACHING AND A DISTRICT HOSPITAL

A teaching hospital is distinguished from a district hospital by the following characteristics:

1. The Standard of Medical Care.

   This is usually higher because the leading members of the medical and nursing profession mainly practice in teaching hospitals. There is critical comment from students and postgraduates re the standard of patient care backed by high technology and clinical research. The staff of district hospitals do not have the same critical approach and they are not exposed to the same peer review. This is not to denigrate the high standards of care which occur in the majority of district hospitals.

2. Case-mix Complexity.

   There is a greater range of complicated and unusual medical disorders. Complicated medical problems are often referred from district hospitals. The staff at teaching hospitals become more adept at treating these difficult problems. The case-mix complexity might be expected to be an important factor in the costs of teaching hospitals (Ament, Kobrinski and Wood, 1981).

3. Super-Speciality Units

   The staff of teaching hospitals are initiators and pioneers in the changes of modern medical care. As a result specialised units and sophisticated medical equipment develop in these institutions.

4. Teaching

   The presence of students, undergraduate and post-graduate medical, nursing and paramedical raises standards. They ask questions, and provide constant clinical audit.

5. Clinical Research

   Improvements in patient care can only be made if there is continuing medical research. This is part of the tradition of all great teaching hospitals. It requires a nucleus of keen thinking hospital staff who will respond to questions, criticisms and the latest overseas and local research.

6. Leadership Role

   The staff of district hospitals look to the teaching hospitals for leadership, guidance and advice re changes in modern patient care. Techniques and changes in patient care developed in the teaching hospital will eventually be applied in the district hospital and in the community.

7. Tradition

   There is a tradition in all great teaching hospitals of the pursuit of excellence. This is not generally to be found to the same degree in a district hospital.

8. Bioethics

   The teaching hospitals with a strong Christian tradition, are particularly concerned with maintaining Christian ethical principles in a scientific humanistic society. They are the leaders in grappling with many of the bioethical problems caused by rapid social and scientific change.

The character of a teaching hospital has been well summarised by Sir William Osler: "The work of an institution in which there is no teaching is rarely first class. There is not that keen interest, nor the thorough study of cases nor amid the exigencies of busy life is the hospital physician able to escape clinical slovliness unless he teaches and in turn is taught by assistants and students. It is I think safe to say, that in a hospital with

students in the ward, the patients are more carefully looked after, their diseases are more fully studied and fewer mistakes are made" (Aequanimitas, 1906).

THE UNIQUE ORGANISATIONAL SETTING OF TEACHING HOSPITALS

Teaching Hospitals are best understood in the context of their unique organisational setting (Butler, Bentley & Knapp, 1980). This has three major characteristics:

1. Multiple Objectives.

These are patient care, education and clinical research. The success of a teaching hospital in meeting its mission is dependent on an ongoing critical review of the standard achieved with each of these objectives. The interdependence of these functions requires skillful decision making and resourse allocation. The potential to excel in any one of these areas is extremely limited if performance in the others is mediocre.

2. External Controls.

There are multiple external organisations and agencies that influence the teaching hospital. There is government control by the State and Commonwealth health departments. The Universities have an important influence through appointment committees, boards of studies, academic departments and the student body. The Royal Colleges establish standards and requirements with regard to graduate education which influences intern and registrar programmes. The Nurses Registration Board regulates nursing education. Medical benefit organisations and medical insurance schemes have lead to expanded revenue and accounts departments unheard of in the days of the charitable hospital. Unions demand awards for lay and paramedical staff, nursing staff, residents, registrars and even full time medical staff. Finally, research organisations such as the National Health and Medical Research Council and the National Heart Foundation, regularly review both the standards and the ethical principles of research within the teaching hospitals.

3. Complex Medical Authority Structure

Patients in a teaching hospital are treated by a large number and variety of medical staff. There are visiting staff, full time and part time staff specialists and academic staff with limited rights of private practice, physicians in training, residents, fellows and multiple health professional groups. All participate in the care of patients. The relative role of each is not always clear. There are divided physician loyalties - institutional (hospital versus medical schools) and physician groups (with varying concerns for patient care education, research and administration). This calls for complex management, decision making processes. The three dimensions of this organisational environment have varying impacts depending upon the institution.

THE PROBLEMS OF THE TEACHING HOSPITAL TODAY

1. Misunderstanding

There has been criticism of teaching hospitals by health economists, administrators, the medical profession, bureaucrats, politicians and enthusiasts for community health care. Much of this criticism comes from people who have no knowledge of the development and the role of teaching hospitals. They have never been in a teaching hospital and have no experience of patient care. Teaching hospitals must respond to this criticism. They will respond in different ways according to their particular super speciality and community roles. Unfortunately, some health authorities would wish to bring all hospitals down to a level of mediocrity. These problems would be less if there was a regular interchange of lay and medical administrators between health departments, district hospitals and teaching hospitals.

2. University Clinical Departments

Historically,teaching was added to the role of most of our present teaching hospitals. The University clinical department was grafted onto the hospital structure initially in the thirties but mainly in the fifties. It was usually seen as a separate service unit in the British tradition (Peart, 1970). The expansion of academic departments since the early fifties has lead to some difficulties between academic and visiting staff. This is gradually changing. In many teaching hospitals the academic staff are now well integrated with other members of the medical staff and occupy positions as rotating chairman of divisions and directors of medicine and surgery. This is a move from the British tradition to the American practice where the chiefs of staff, especially in medicine and surgery, are usually full time professors. This was suggested by Blackburn (1965) in the 1960s. It is advantageous provided the professor is weighed down by political and financial problems and lack of adequate administrative support as described by Petersdorf (1980). The funding of these departments remains hazy and often a contentious issue between hospital, university and Departments of Health and Education.

During the period 1953 to 1981, there has been an enormous growth of full time staff specialists and academic clinical staff in Australian teaching hospitals. There are 123 (June 1980) full clincial professors in Australia and approximately 1200 associate professors and senior

lecturers. This has had an effect on the role, number and quality of those available for appointment to the visiting staff. The result has been a reduction in the influence of the visiting staff in teaching hospitals leading in some cases to ill feeling, frustation and problems in staff relationships (Andrew, 1972).

3. Hospital Staff and the University

There are advantages to the hospital, the University and the individual in fuller participation by medical staff in the university environment. In recent years, full time hospital staff specialists have been increasingly appointed to conjoint positions which give them an equivalent university status at senior lecturer or associate professor level. However, in most medical schools, the problem of integration of the many excellent members of the visiting staff remains unresolved. This is surprising as they provided the initial clinical staff of our medical schools and there were no full time clinical professors until 1930. Academic colleagues in universities do not understand the complicated medical system and are often threatened by the university medical faculty with its large component of off campus staff. University/hospital relationships have been a continuing problem in all countries and in all hospitals since teaching hospitals began. The town and gown problem is not easily resolved.

4. Geographic Full Time Staff

In the past the visiting staff, for economic reasons, were often attached to several hospitals. With the gradual development of medical centres there is an increasing tendency for the part time staff to become geographically full time. This must be encouraged and should become mandatory for appointment to a teaching hospital.

5. Chairmanship

The lines of command and responsibility in many departments in teaching hospitals are traditionally blurred. This is again historical and related to the "Honorary system" and partially to a lack of modern administrative methods. Some of these problems have been highlighted by B. Hudson in his A.W.T. Edwards oration (Hudson, 1971). Who is chairman? Is he to be appointed or elected? Is the appointment made on the grounds of years of service or administrative ability? Who is responsible for the hiring and firing of both medical and lay staff - the chief of the division or the lay or medical administrator of the hospital? Who has the ultimate responsibility for seeing that all members of the staff fulfil their duties with regard to patient care, teaching,research and administration?

6. Appointments in Perpetuity

The problems of administration and responsibility are accentuated by appointments in perpetuity, of visiting medical staff, staff specialists and academics.

7. Administrative Structure and Medical Staff Organisation

Teaching or referral hospitals are the most complex of hospitals and have a place amongst the most intricate organisations society has derived. The administrative structure of many of our teaching hospitals with annual budgets in excess of $5-10 million is unsatisfactory (Duckett, Scarf, Schmiede, Weaver, 1981). It is not comparable to similar organisations in industry and the hospital board is not responsible to its share holders. Hospital boards although enthusiastic are too often composed of retired business men with little experience or understanding of hospitals and medicine. Up until recently there has been too few of the young executive type with experience and or degrees in commerce and economics. Further the members of such boards are often uncertain of their role, the hospital objectives, and the principles of hospital management.

The lay administration of hospitals is sadly lacking in those with imagination and real economic and management skills. Medical administrators have too often been medical graduates who have drifted into medical administration as a compromise from other careers. Fortunately, there is a gradual change in both of these areas. Job specifications need to be made more attractive to bring very able people into this difficult area of administration. As already mentioned there is also a real need for more interchange of staff between teaching hospitals and regional and central health administration. Visiting, part-time, full-time and academic medical staff are an awkward group to integrate and lead. Their administration is difficult when the majority are not salaried staff of the institution and have a varying degree of committment to the hospital beyond limited patient care.

8. Communication

This is a major problem within the complex hospital structure, and outside with Health Departments and the medical and lay community.

9. Teaching and Case Mix

The development of large district hospitals in outer suburbs and the concentration of specialist units in teaching hospitals has changed the case mix in teaching hospitals in the last twenty years, especially in New South Wales and Victoria.

This meant that the student is less likely to see common medical and surgical conditions and was the subject of considerable discussion in the seventies (Ewing, 1972; Med. J. Aust., 1972). It has to some extent been overcome by the use of associated teaching hospitals and elective terms. The increasing trend to private hospitals, especially for elective surgery, may accentuate this problem in future.

10. Funding and Expenditure

The funding of teaching hospitals is complex. Funds come from multiple sources. There is a continuing saga of fiscal crisis compounded by weak management, poor accountancy, limited prerogatives, lack of an identifiable stewardship and no reward for efficient management. Health departments should reward efficiency and not regularly "bail out" teaching hospitals that overspend. This has been a nagging problem in both N.S.W. and Victoria. The expenditure on teaching hospitals makes up a large percentage of the total public hospital expenditure. This varies from state to state (Table 3). New South Wales has the lowest national expenditure on teaching hospitals and the highest expenditure on non-teaching hospitals, but there is an appreciably higher cost/occupied bed/day in teaching hospitals (Table 4). The high cost of teaching hospitals is not related to undergraduate teaching but is more related to the complicated case mix and the development of high technology and associated staff salaries (Ament, Kobrinski & Wook, 1981). This has also led to increased hospital costs in non-teaching large district hospitals (Andrews, 1976). Even within one state there may be unusual differences in cost/occupied bed/day. The variation between the costs/occupied bed/day for the four major teaching hospitals associated with the University of Sydney as compared with the University of New South Wales (Table 5) are not easily explained on the basis of bed numbers, bed occupancy, case mix or student numbers. Teaching hospitals and health departments need to constantly look critically at the control of these costs without lowering the standards of health care. The disagreement between Health and Education departments re the costs of health care and teaching of medical students,nurses and paramedical staff must be resolved. Alternatively, as in Britain teaching hospitals should receive special funding from a federal body.

11. Laboratory Tests

During the seventies the excessive use of laboratory tests was one of the factors that increased health costs. This world wide trend began in patients hospitalised in the teaching hospitals and was transferred to district hospitals and community practice. Strenuous efforts both locally and overseas have halted and are reversing this trend (Grimer, 1979). Continued administrative and educational strategies directed towards optimum use of the laboratory must be maintained in the teaching hospital.

THE FUTURE OF THE TEACHING HOSPITALS

Teaching hospitals are an essential and vital part of helath care delivery and health education. In order to cope with rapidly changing medical care in a no-growth limited finance society they must be efficient, innovative, imaginative, adaptable and communicative. This has not been their outstanding characteristic in the past or present but is consistent with their historical development.

The change must start at the top. Health and education authorities must agree to work together re objectives and funding. Health department administrators must be constructive and not destructive. The teaching hospital board must be composed of efficient administrators, accountants, and representatives of the university and medical staff. The hospital administration should be in the hands of those lay or medical personel recognized for their administrative skill and imagination and they must be paid accordingly. The medical and nursing staff organisation must be reviewed and reorganised so as "to be a relection of interaction of the hospitals' historical development, the influence of key individuals who currently hold power, the communication mechanisms developed to consider the issues, the recently technological developments within the hospital, and its plans for future developments and the economic and political environment within which the hospital operates" (Duckett, Scarf, Schmiede & Weaver, 1981).

There must be regular reviews of medical, nursing and lay staff with reference to individual contributions to patient care, teaching, research, and hospital function. Teaching hospitals do not function for the good of the staff. Their functions are patient care, teaching and research.

Funding for capital costs, salaries, rebuilding, replacement and additional high technology equipment will be a continuing problem. This requires imagination and the co-operation of government, private institutions, industry and individuals. The limited public service - treasury financial mentality will not be able to cope with the high-cost medical technology of the future. It must be replaced with a co-operative compromise.

Change must and will occur but in this environment the traditional high standard of patient care in teaching hospitals must be maintained. It has developed over 100 years in many famous Australian teaching hospitals. It has played a vital educative and research role in producing the high standard of medical and nursing care for which we are world renowned.

The words of John Billings as he opened the John Hopkins Hospital, Baltimore, in 1889 are applicable to the Australian teaching hospital today. "The teaching hospital is a living organism made up of many different parts having different functions, but all these must be in due proportion and relation to each other and to the environment to produce the desired general results. The stream of life which runs through it is incessantly

TABLE 3

PROPORTIONS OF PUBLIC HOSPITAL EXPENDITURE IN TEACHING AND NON-TEACHING HOSPITALS, 1976-77 *

	STATES						
	NSW	VIC	QLD	SA	WA	TAS	AUST
No. of Teaching Hospitals	10	12	9	6	5	2	50
Proportion of Expenditure in Teaching Hospitals	34.2	51.8	56.2	71.9	69.3	55.7	59.5
No. of Non-Teaching Hospitals	234	142	135	73	91	20	709
Proposition of Expenditures in Non-Teaching Hospitals	65.8	48.2	43.8	28.1	30.7	44.3	50.5

* Jameson, 1980.

TABLE 4

COST/OCCUPIED BED/DAY *

NEW SOUTH WALES 1980-81

State Average	$135.79
Teaching Hospitals	$170.17
Non-Teaching Hospitals (10)	$124.63

* Health Commission of New South Wales Statistics and Financial Data Public Hospitals 1980-81

TABLE 5

COST/OCCUPIED BED/DAY *

NEW SOUTH WALES 1980-81

HOSPITALS		
Royal Prince Alfred		$193.25
North Shore		$196.94
Sydney		$199.45
Westmead		$223.74
	Av. $203.34	
Prince Henry-Prince of Wales		$185.18
St. Vincent's		$177.02
St. George		$148.32
	Av. $170.17	
	Overall Average	$189.12

* Health Commission of New South Wales Statistical and Financial Data Public Hospitals 1980-81

changing; patients, nurses and doctors, come and go. Today it has to do with the results of an epidemic, tomorrow with those of an explosion or fire. The reputation of its physicians or surgeons attracts those suffering from a particular form of disease and as one changes so do the others. Its work is never done; its equipment is never complete; it is always in need of a new means of diagnosis, of new instruments and medicine; it is to try all things and hold fast to that which is good" (Strauss, 1968).

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(Manuscript received 28.9.1983)

Journal and Proceedings, Royal Society of New South Wales, Vol. 116, pp. 141-142, 1983
ISSN 0035-9173/83/020141 — 02 $4.00/1

Speech at the Annual Dinner of the Royal Society of New South Wales*

JOHN M. WARD

Mr. President, Ladies and Gentlemen,

I am grateful to have the honour of moving your Toast tonight. At The University of Sydney the Vice-Chancellor belongs to each and every Faculty. He is required to ba a scientist and a lawyer, a physician and an engineer, a dentist and a humanist. In this circumstance I want to move your Toast by reminding you of your origins and of the close relations between your origins and the foundation of The University of Sydney. There is no more fitting place to do so than in this famous Great Hall, that was completed in 1859.

The sixth Governor of New South Wales, Sir Thomas Brisbane, was a scientist as well as a soldier. His interest in astronomy was and still is well-known. When he came here in 1821 he brought with him scientific equipment and also a good astronomer, Dr. Charles S. Rumker. Brisbane, when not watching the southern skies, was a sociable person and took an active role in establishing the predecessor of the Royal Society of New South Wales. In the year of his arrival and with his active encouragement there was formed the Philosophical Society of Australasia.

The grand name indicated objectives and intentions, rather than actual achievements. In its early years the Society was a small scientific club of not more than ten members, who met in one another's houses, read papers and discussed science in its broadest aspects.

The members were united in a belief that Australasia offered a uniquely challenging field to scientific enquiry. "When we consider that we are speaking in the nineteenth century", they announced, "and reflect on ... the rejection and adoption of various systems of every branch of natural history, and the security which, it was fancied, that scientific arrangement had at last attained, we are almost inclined to believe that Nature has been leading us through a mazy dance of intellectual speculation, only to laugh at us at last in this fifth continent". With so much new to discover and to classify, the members proposed to exchange information with one another and with learned bodies overseas. They also did honour to Captain James Cook and to Sir Joseph Banks, who had come to Australia with Cook as a freelance gentleman botanist, and who was President of the Royal Society for forty years.

That little club of gentlemen, united in the pursuit of scientific knowledge, resolved that "polemical divinity and party politics" should be forever excluded from its proceedings. Despite that attempt at built-in security, the Society expired after only one year. Its members had been very much in earnest. They had charged one another £5 admission fee, six shillings for non-attendance, and £10 for failing to read a paper when scheduled to do so. Those were good strong penalties and not even dinner at Government House was accepted as an excuse for not reading a paper.

What threw this zealous band of amateurs into disarray was, in the words of one of its members, Judge Barron Field, "The baneful atmosphere of distracted politics". There was in fact a mixture of financial crisis and political controversy, such as has been known before and since; the members had too many urgent problems of their own to continue meditating on the problems of science. The Society expired, not with a bang, but a whimper.

One of the founding Fathers of this first Society had been Henry Grattan Douglass, a medical doctor. He was, indeed, the Society's Foundation Secretary. In some ways his own troubles probably helped to put his beloved Society into what its friends called "suspended animation" and its critics called death. Douglass was publicly charged with having maintained improper relations with a comely convict lass, Ann Rumsby, whom he had taken into his household. The incident and others of a more directly political kind that followed, at least showed how public and private affairs were as closely mixed up with one another in colonial Sydney as they are today. Douglass was away from the Colony from 1828 to 1848 and on his return set about two important tasks, that are highly germane to the toast that I am to move tonight.

Douglass had decided that New South Wales needed a university, further, that the Philosophical Society, which he saw as the intellectual companion of the University, should be revived.

The Society was revived in 1850, the year in which the Act founding The University of Sydney was passed. In its new form the Society was called the Australian Philosophical Society and its objects were rather different from those of the original body. Applied science was emphasised in the statement of objectives: "the encouragement of Arts, Sciences, Commerce and Agriculture in Australia". "Arts" meant not the humanities, but the applied Arts. The Society treated itself as continuous with the original Society of 1821-22. Its Patron was the Governor-General, Sir Charles Fitzroy, who was also the Visitor of The University of Sydney. The Vice-Provost of the University, Sir Charles Nicholson, was Vice-President of the Society.

In 1855, after the Gold Rushes had subsided and after Victoria had been separated from New South Wales and Moreton Bay had begun its movement for separation, the Society changed its name from the Philosophical Society of Australia to the Philosophical Society of New South Wales. According to Professor Elkin, who wrote a paper on the history of the Royal Society, the peak year of the Philosophical Society was 1858, with 186 members.

* Speech by the Vice-Chancellor and Principal of the University of Sydney, Professor J.M. Ward at the Annual Dinner of the Royal Society of N.S.W., held in the Great Hall, Wednesday, 2nd March, 1983.

A decline followed until the doldrums of the early 1860s produced through decisive acts of leadership the Royal Society itself.

Our best guide is the Reverend W.B. Clarke, Vice-President of the Philosophical Society and its acknowledged leader. Clarke was a geologist of good standing, who feared that the Philosophical Society would never attract support in a colony where leisure was "generally given to the frivolities of ephemeral excitement ... sensational knowledge ... and railway literature", whatever that might have been, probably the mid-nineteenth century counterpart of paperback fiction. Clarke believed that the name "philosophy" scared people away. Already philosophy and natural philosophy had grown apart at least so far as the general public was concerned. Clarke himself was a clergyman; he was also an empirical scientist, and something of a politician. He advised the Society to give up speculation about the nature of the universe, and to concentrate on making discoveries in "things visible, hoping thus to obtain an insight into which mere Philosophy can never reach". With a large concession to the commercial spirit of the age, he added: "We ought to be labouring for the development of the physical character of the country we live in", to discover its natural history and its resources, "since this appears to be now admitted as the special object of our researches".

For these reasons the name "Philosophical" was dropped from the Society's title and the name "Royal" was inserted in its place. The Governor, Sir John Young, made the necessary representations to Queen Victoria and on 12 Sepatember, 1866, the last meeting of the old Philosophical Society and first meeting of the Royal Society of New South Wales was held. The Fundamental Rules of the new Society repeated the original objectives of receiving papers on Art, Science, Literature and Philosophy and added "especially on such subjects as tend to develop the resources of Australia, and to illustrate its Natural History and Production".

An Annual Meeting is altogether a suitable occasion for recording one's origins. Is not an annual meeting rather like a birthday? The humble beginnings of the Royal Society of New South Wales were laid by men of goodwill, who belonged to a generation when men took it for granted that science and literature, philosophy and geology were all intricably linked. So they are, and that is why we value so highly the individuals among us who can see the links and stimulate the imaginations through them.

I congratulate the Society on a history of which Douglass and Clarke would be proud and invite you to drink the toast to the Society that we all honour.

The Royal Society of New South Wales!

(Manuscript received 3.11.1983)

Journal and Proceedings, Royal Society of New South Wales, Vol. 116, p. 143, 1983
ISSN 0035-9173/83/020143 — 01 $4.00/1

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JOURNAL AND PROCEEDINGS

OF THE

ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 116

PARTS 1-4
(Nos. 327-330

1983

ISSN 0035-9173

PUBLISHED BY THE SOCIETY
PO BOX N112, GROSVENOR STREET, NSW 2000

Royal Society of New South Wales

OFFICERS FOR 1982-1983

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Parts 1 and 2

Parts 3 and 4

Dates of publication
Parts 1 and 2: August, 1983
Parts 3 and 4: December, 1983

Contents

VOLUME 116, PARTS 3 and 4

Publicity Press (NSW), 66 O'Riordan St, Alexandria, Sydney.